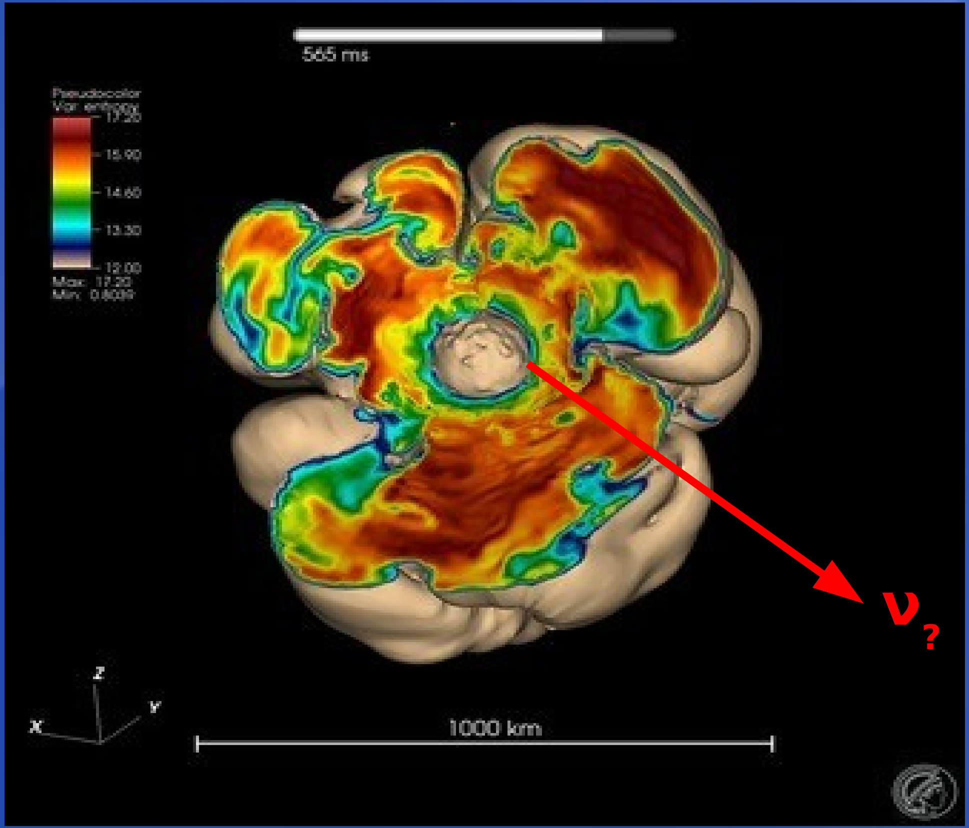
Supernova neutrinos
- flavor evolution and signals

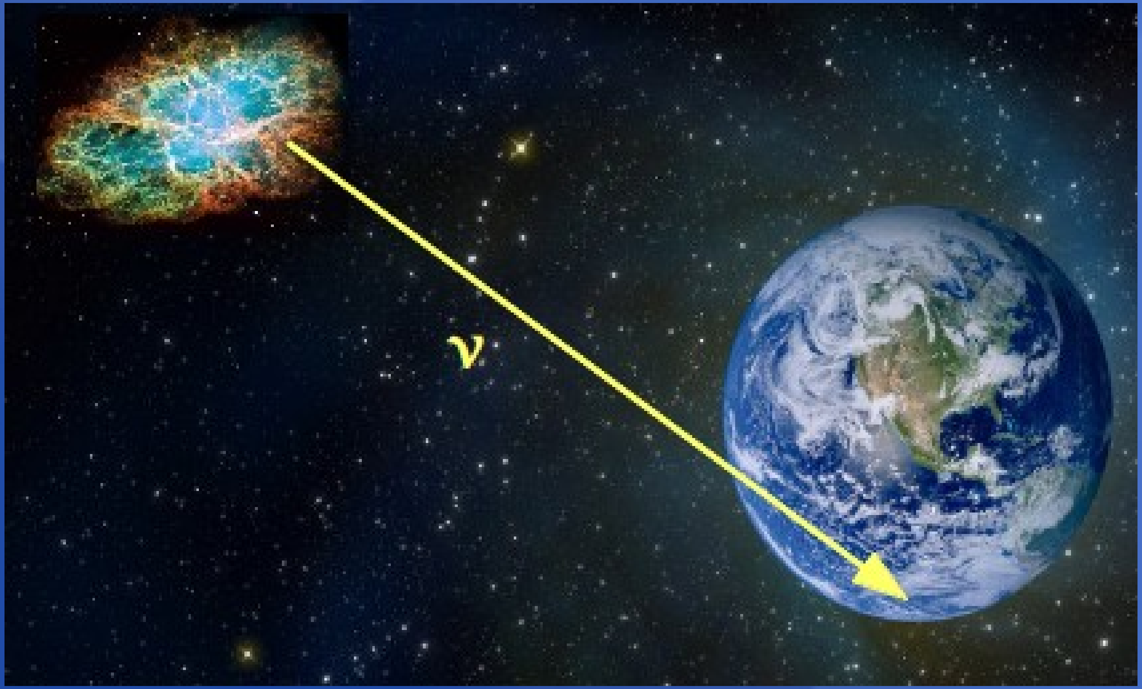


Tina Lund, NCSU

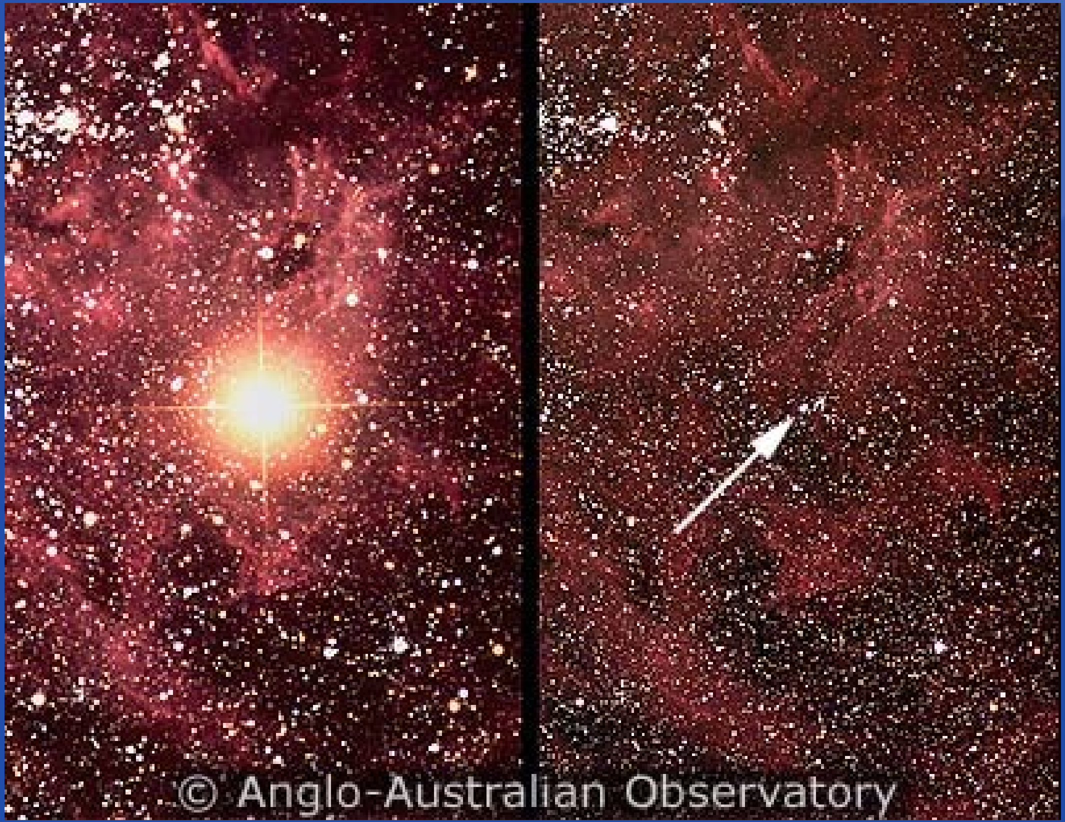
INFO13, Santa Fe, August 28th, 2013

Outline

- Motivation/Intro.
- Flavor evolution in the matter basis – with and without turbulence.
- Signatures of late time flavor evolution in ν observations.
- Signatures of early time explosion mechanism in ν observations.
- Conclusions.



Motivation



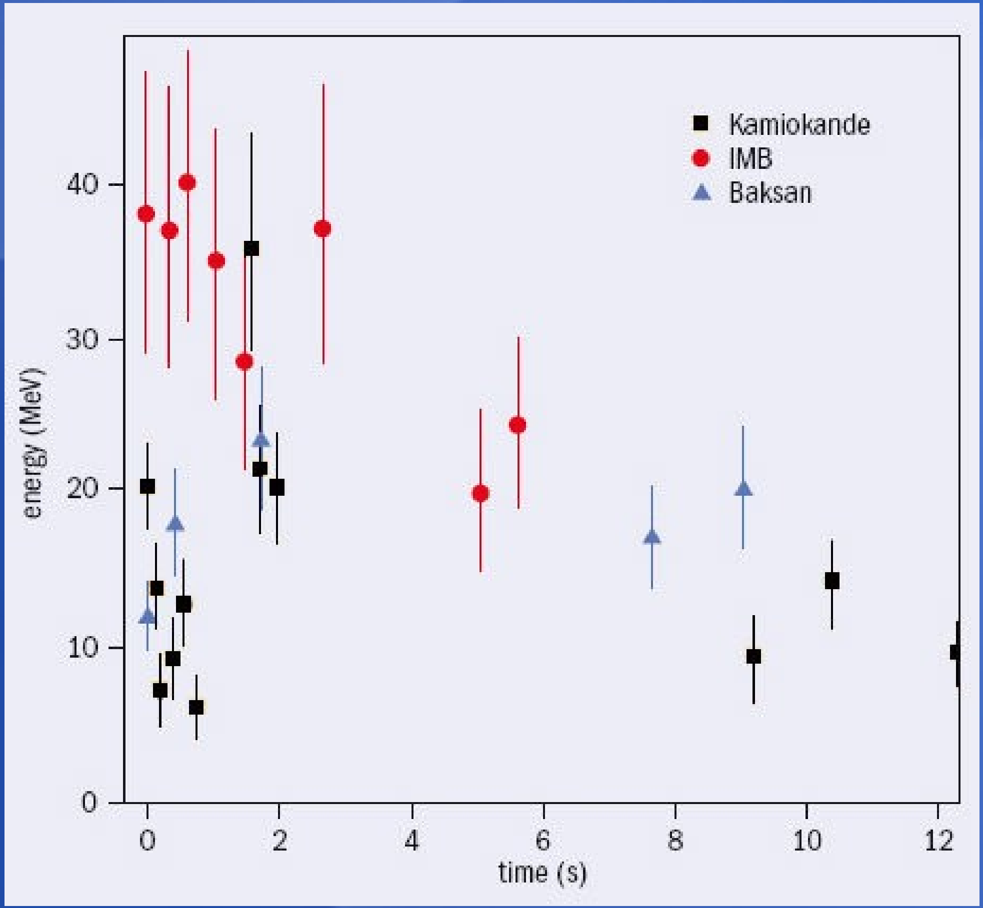
Why are we interested in ν propagation in SN matter?

- Want to understand the core-collapse supernova explosion mechanism.
- Want to use neutrinos to learn about it.
- Want to learn about ν's

Motivation

SN1987A:

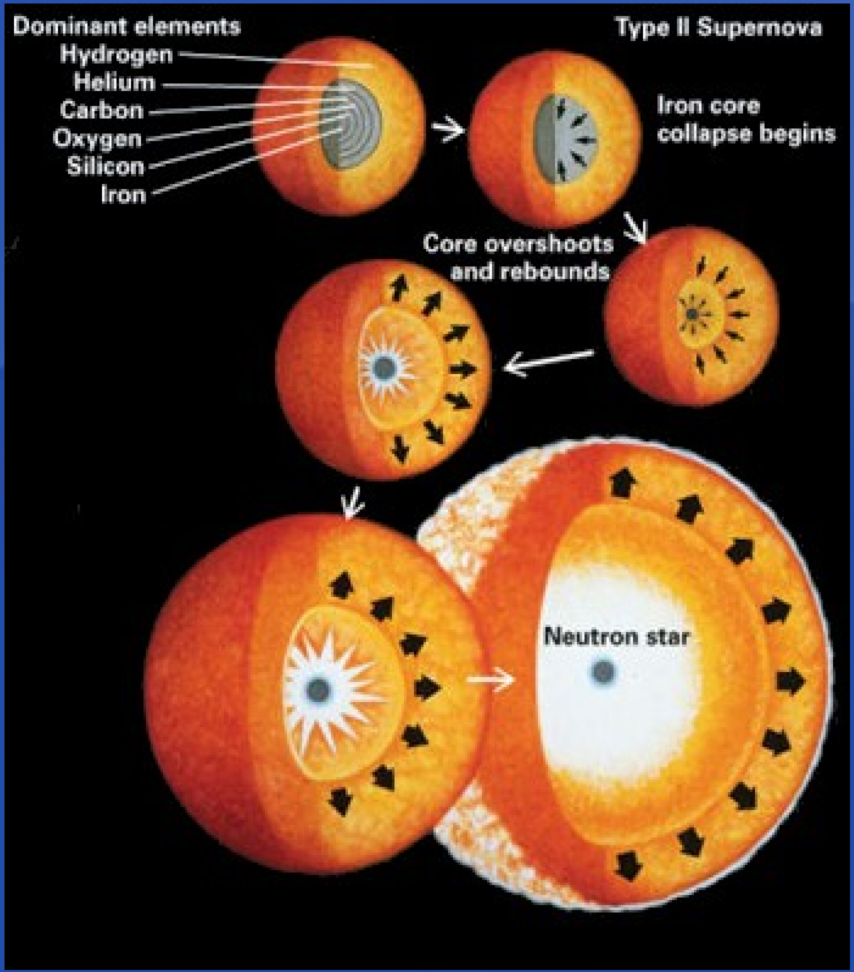
- First observed SN neutrinos → looking inside.
- Details still missing, but overall SN understanding was confirmed.



Aim:

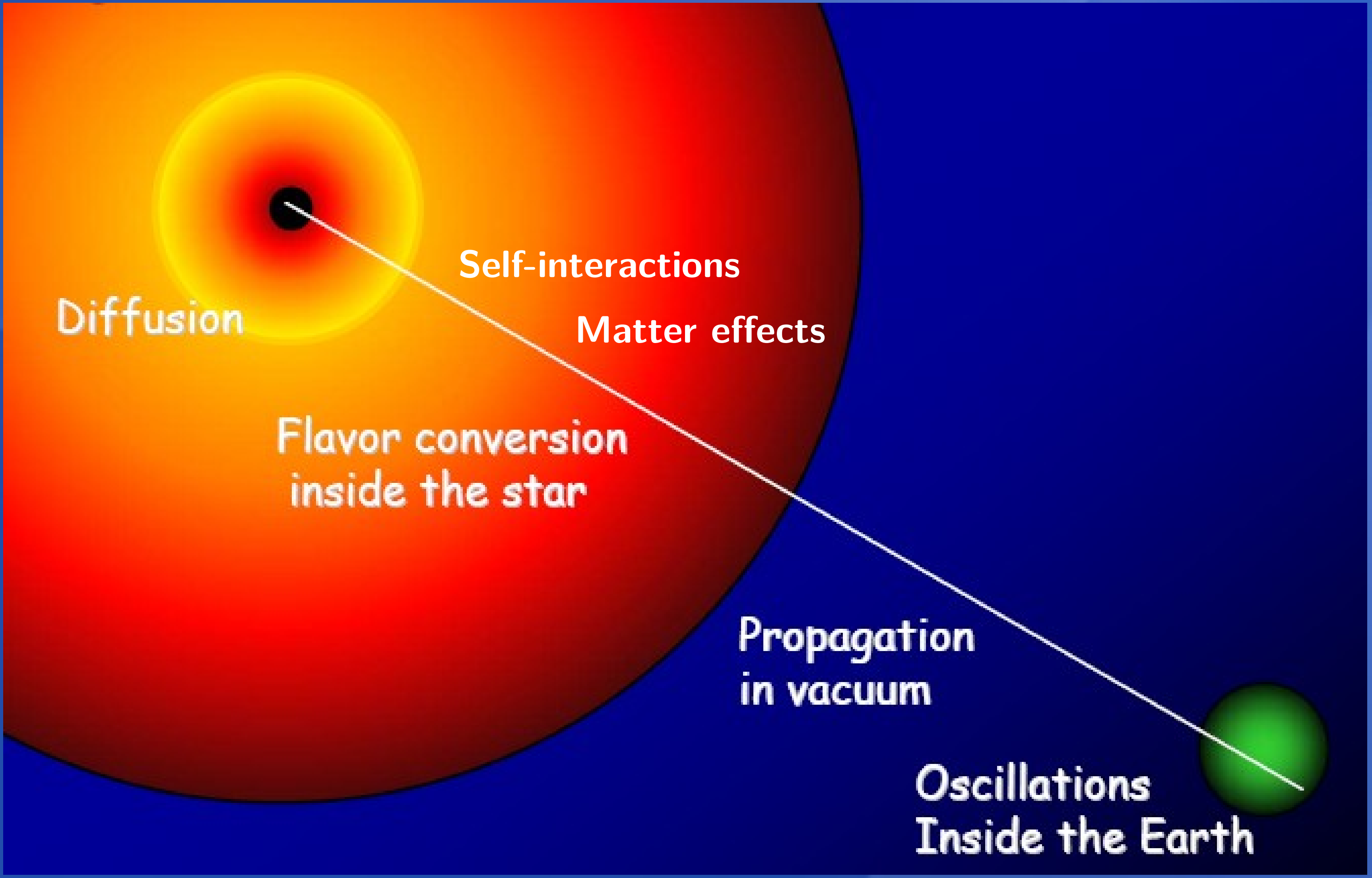
- Understand next observations and neutrinos better.

Core-collapse SN in a (nut)shell



- Stars with masses between roughly 8 and 25 M_{sun}.
- Burning ceases at Fe-peak.
- Onion structure.
- Core collapses gravitationally.
- Infalling material bounces → outward moving shock wave.
- NS cools off and shrinks.
- Wind is compelling site for heavy element nucleosynth.
- ν's emitted through out.

Neutrino propagation



Flavor conversion along propagation

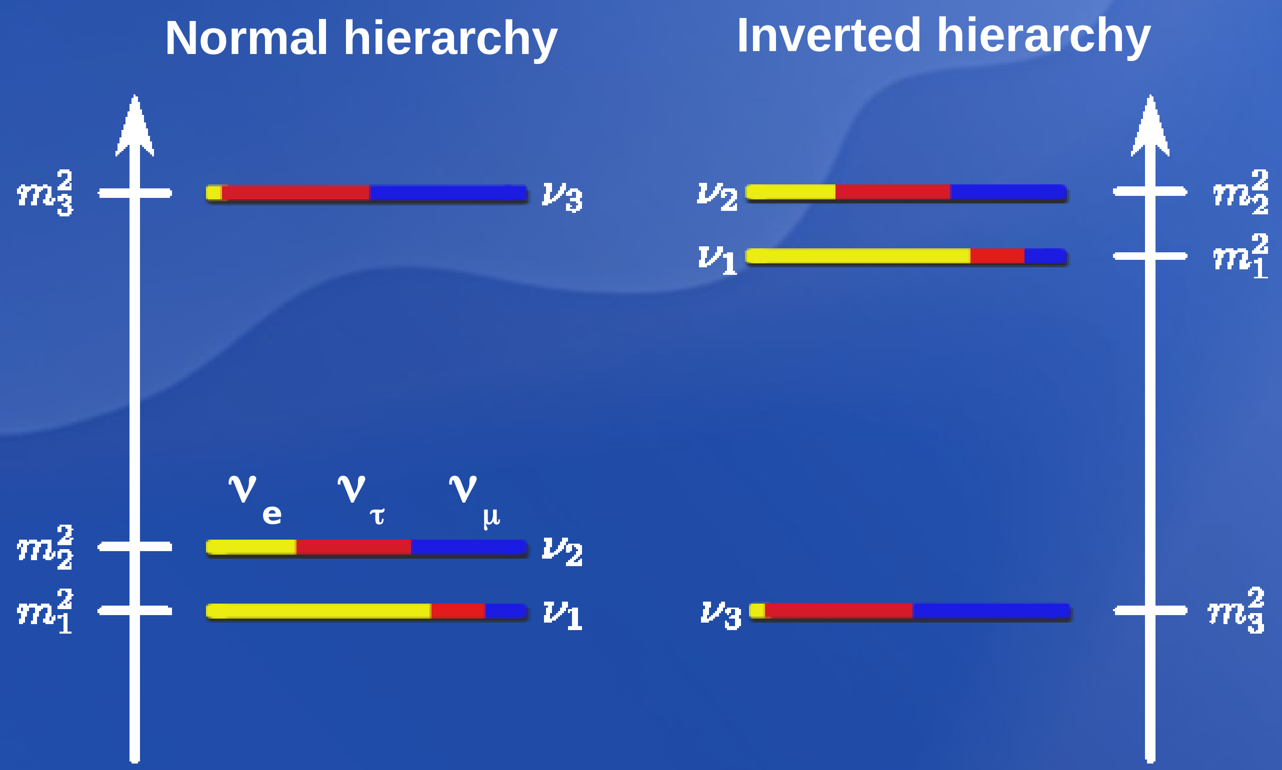
- Flavor eigenstates, $\nu_f \neq$ mass eigenstates, ν_i .
- $\rightarrow \nu$ can change flavor as they propagate.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23}\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{ij} = cos\theta_{ij}$ and $s_{ij} = sin\theta_{ij}$

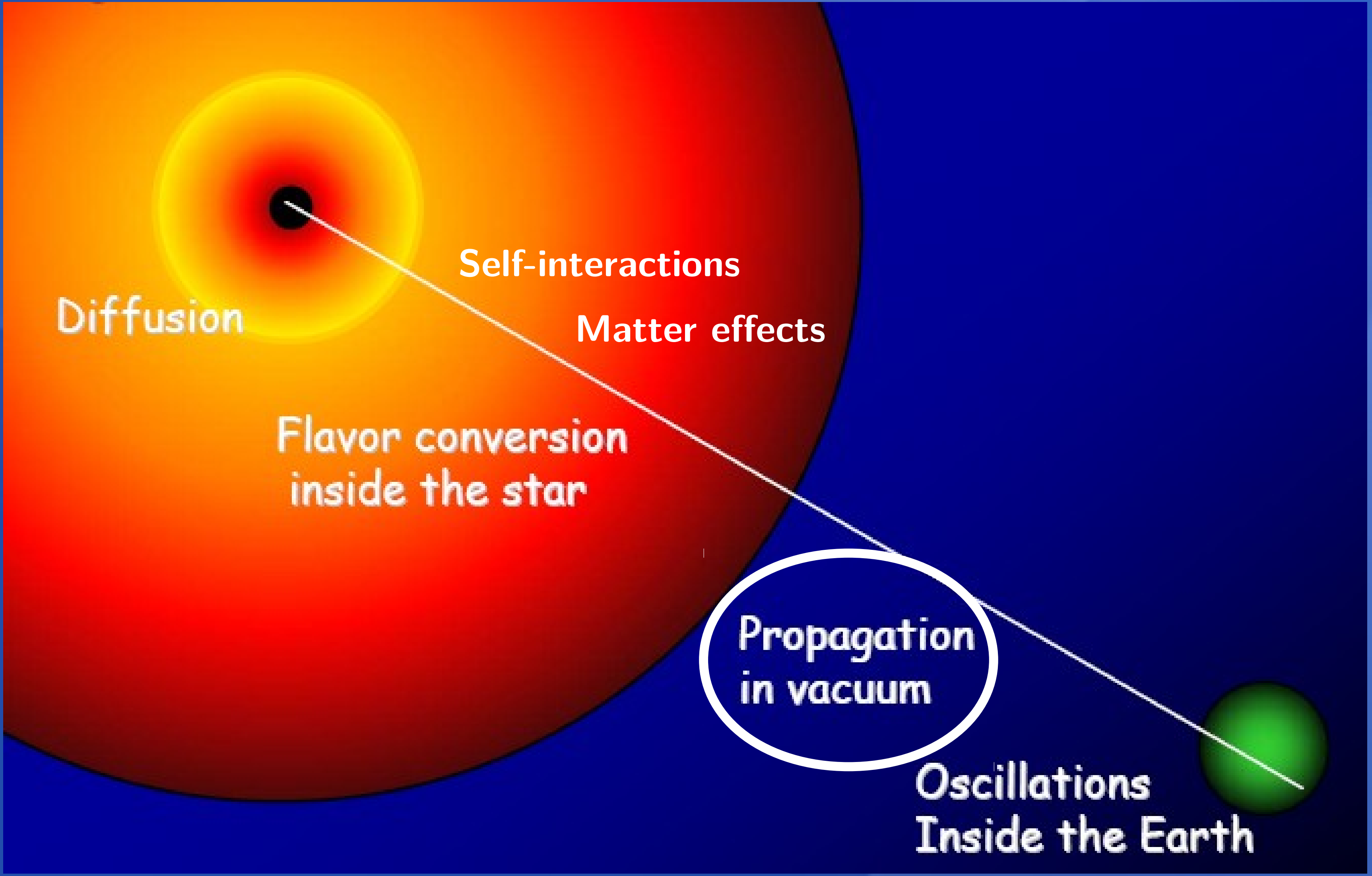
- Mixing angles, θ_{ij} , in matter will depend on the instantaneous density.
- Flavor conversion depends on the hierarchy.

Neutrino mass hierarchies

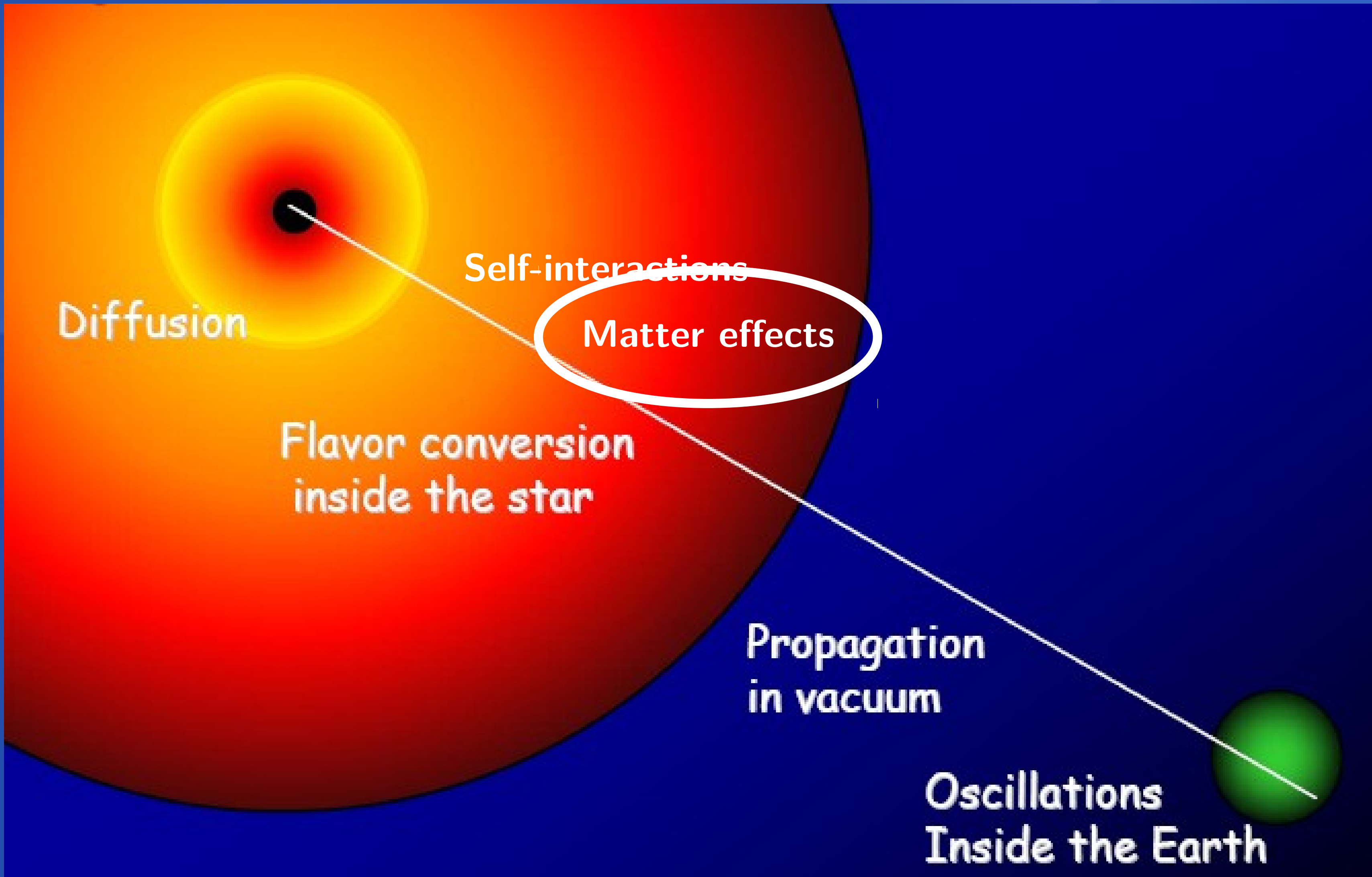


- The hierarchy depends on the sign of the Δm_{13} mass splitting.

Flavor conversion in vacuum



Flavor conversion in the SN



Matter resonances

- Neutrino flavor changes can occur in two density regions:

$$\rho_{res} \sim 1.4 \times 10^6 \text{ g/cc} \left(\frac{\Delta m^2}{1 \text{ eV}^2}\right) \left(\frac{10 \text{ MeV}}{E}\right) \left(\frac{0.5}{Y_e}\right) \cos 2\theta$$

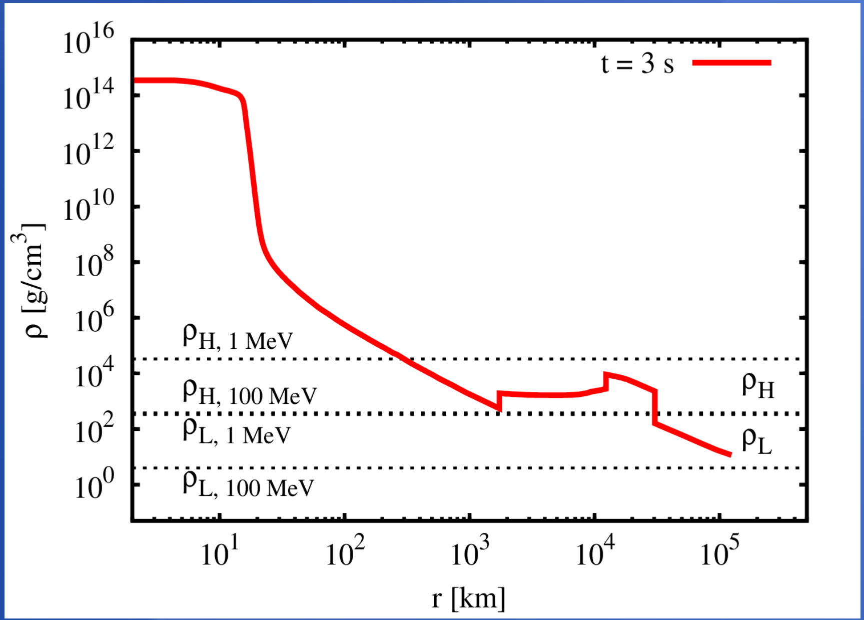
- ρ_H corresponding to

  $\Delta m_{13}^2 \approx 2.43 \cdot 10^{-3}$ eV^2 and $\theta_{13} = 9°$

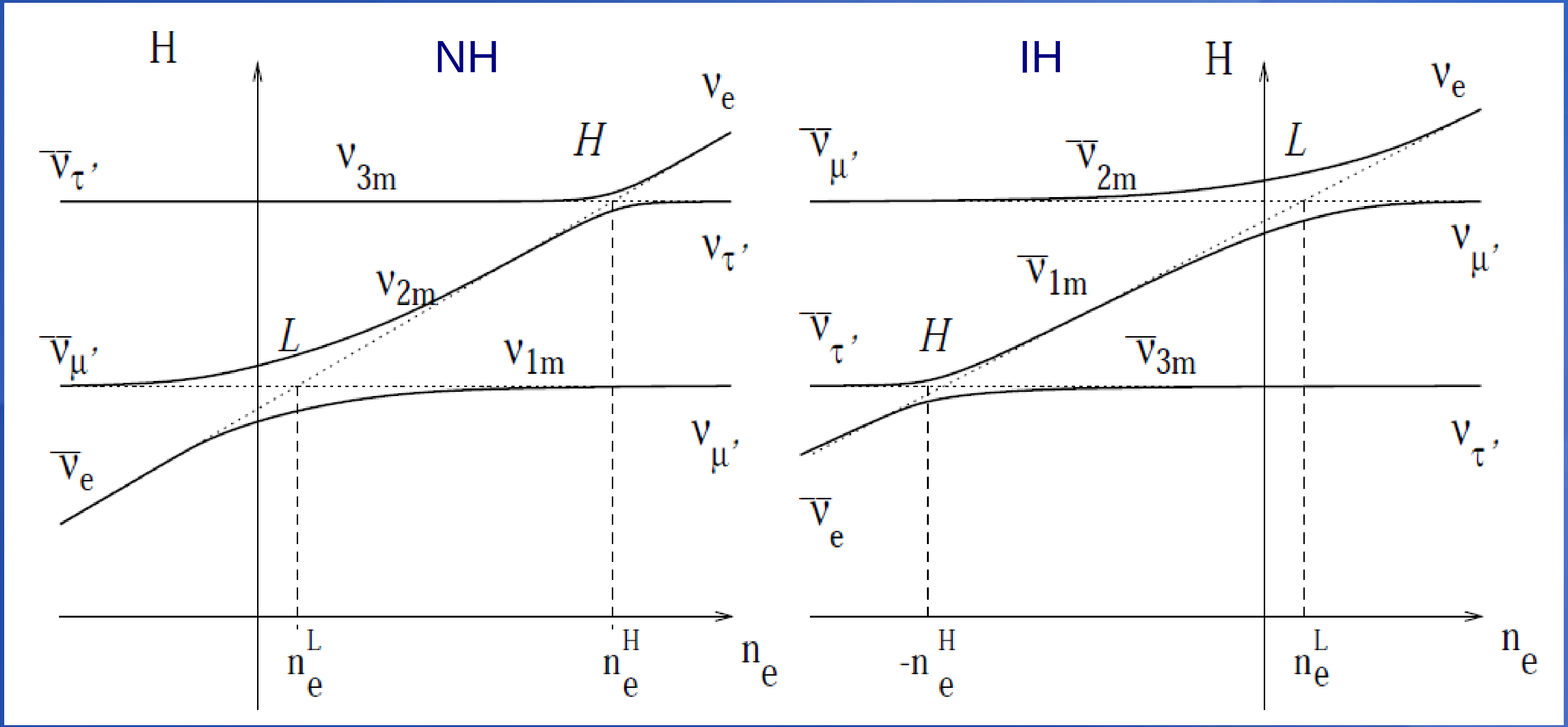
- ρ_L corresponding to

  $\Delta m_{12}^2 = 7.56 \cdot 10^{-5}$ eV^2 and $\theta_{12} = 34°$

- Such flavor changes are called matter or Mikheyev-Smirnov-Wolfenstein (MSW) effects.



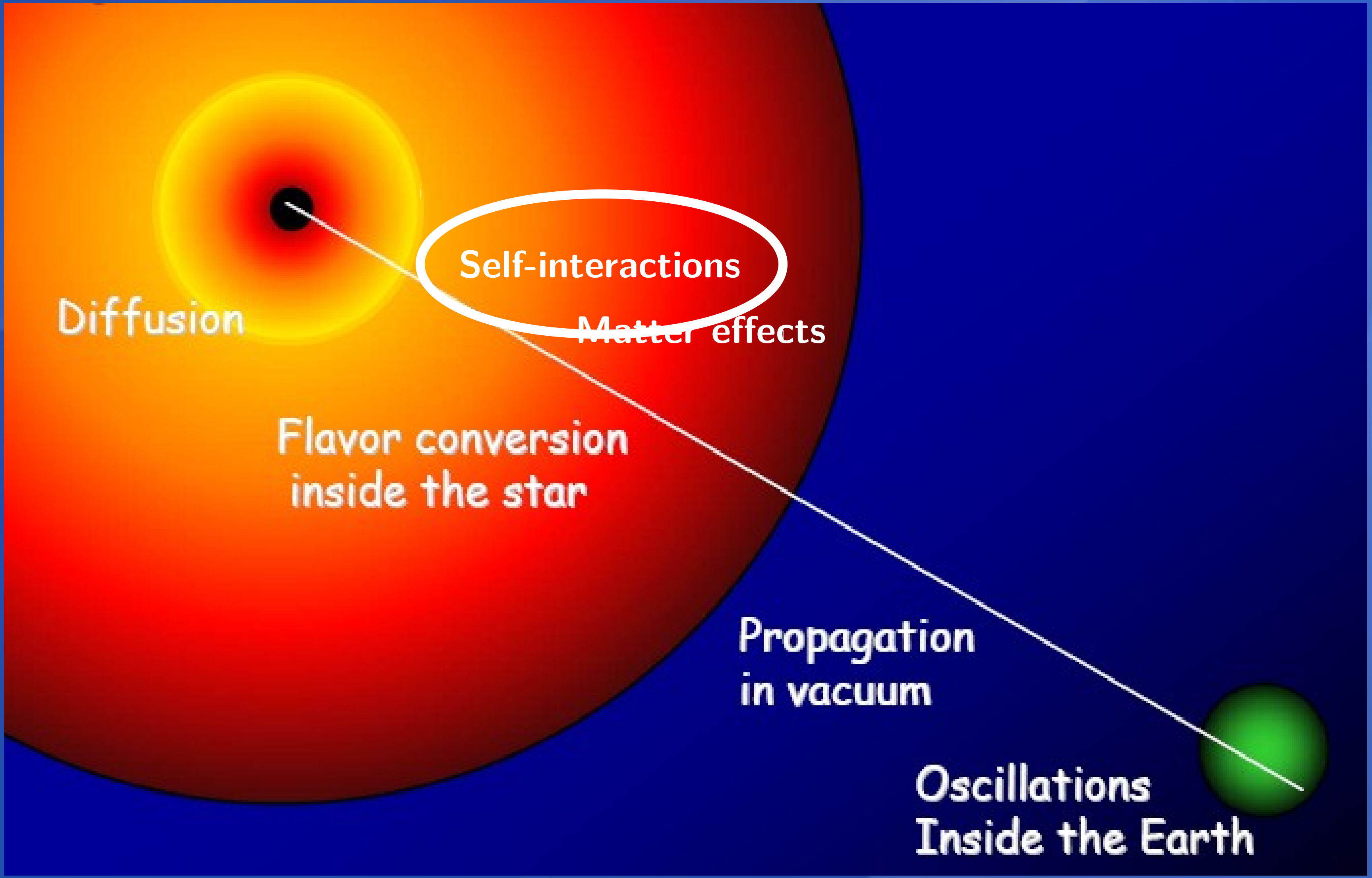
Resonance transitions



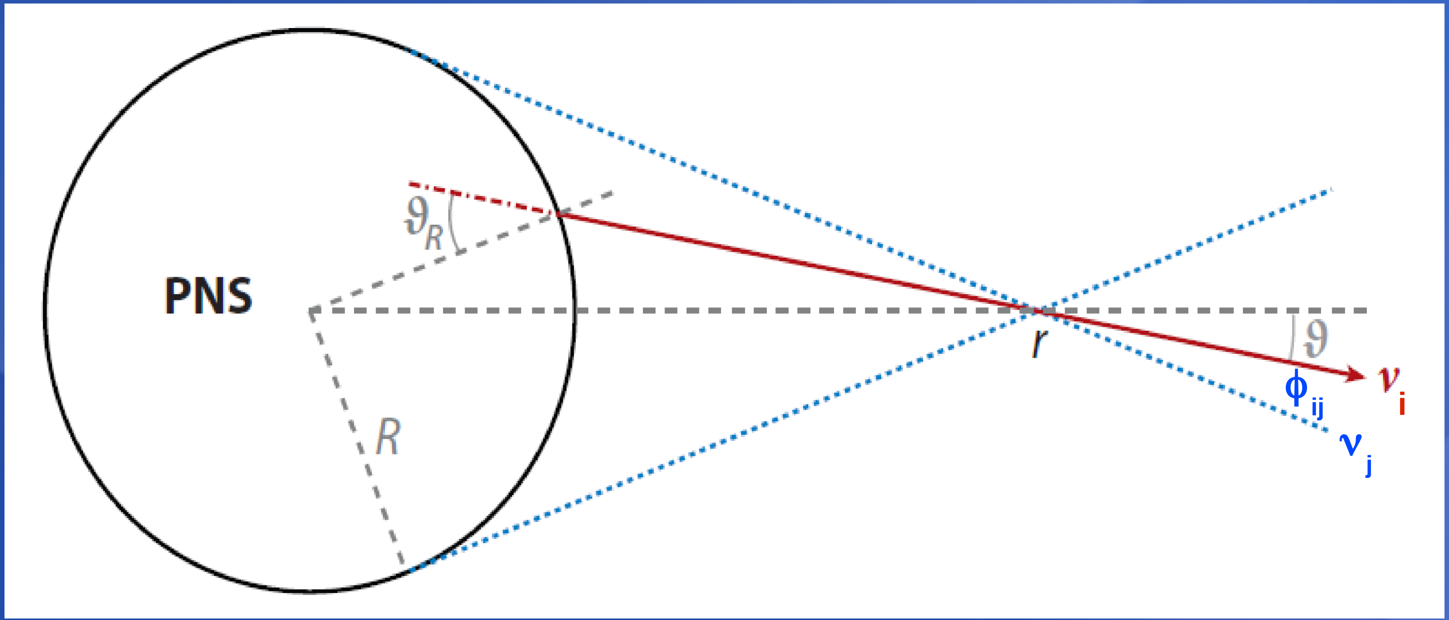
[Dighe & Smirnov, 2000]

- At high densities flavor states equal matter states.
- At resonance, simplified probability is: $P_{jump} = \exp(-\gamma\,\pi/2)$, where $\gamma \propto n_e / (dn_e / dr)$.

Flavor conversion in the SN



Neutrino self-interactions



[adapted from Duan, Fuller & Qian, 2010]

- At high enough neutrino densities n_ν .
- Depends on E_i, E_j, ϕ_{ij} and the flavor of the background ν or $\bar{\nu}$.

Neutrino Schrödinger Equation

$$i\, dS/dt = (H_{vac} + H_{mat} + H_{\nu\nu,i})\, S$$

- Where:

$H_{vac} \propto \Delta m^2/4E_\nu$	vacuum part
$H_{mat} \propto V_e$	matter or MSW part
$H_{\nu\nu,i} \propto \cos\phi_{i,j}\ n_\nu(E)$	self-interaction part
$\Psi_\nu(t) = S(t,t_0)\, \Psi_\nu(t_0)$	evolution operator S
$P_{ij} = \lvert S_{ij}\rvert^2$	transition probability

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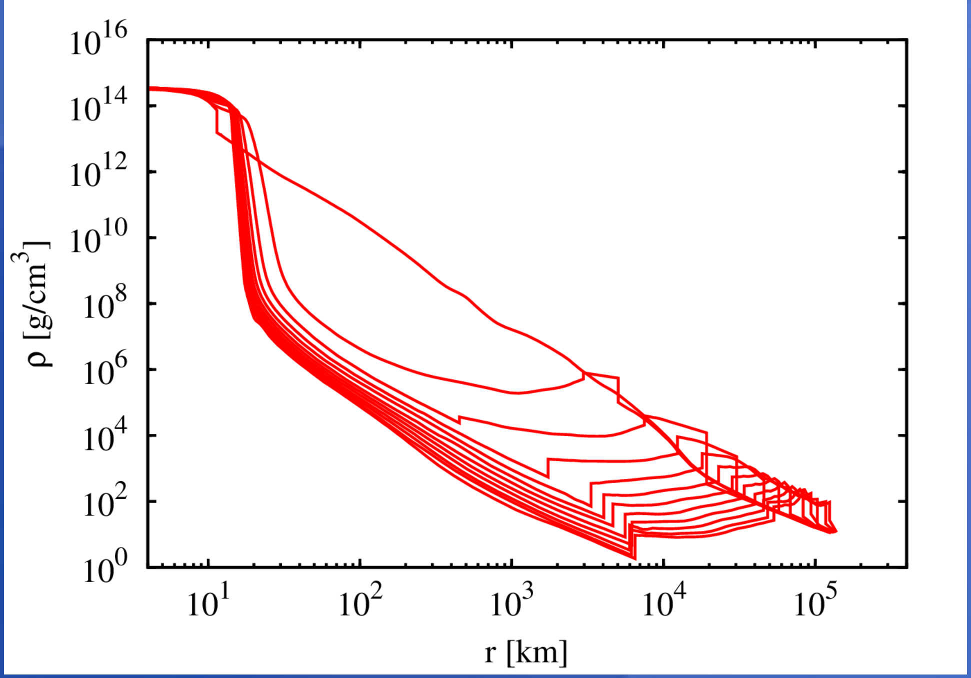
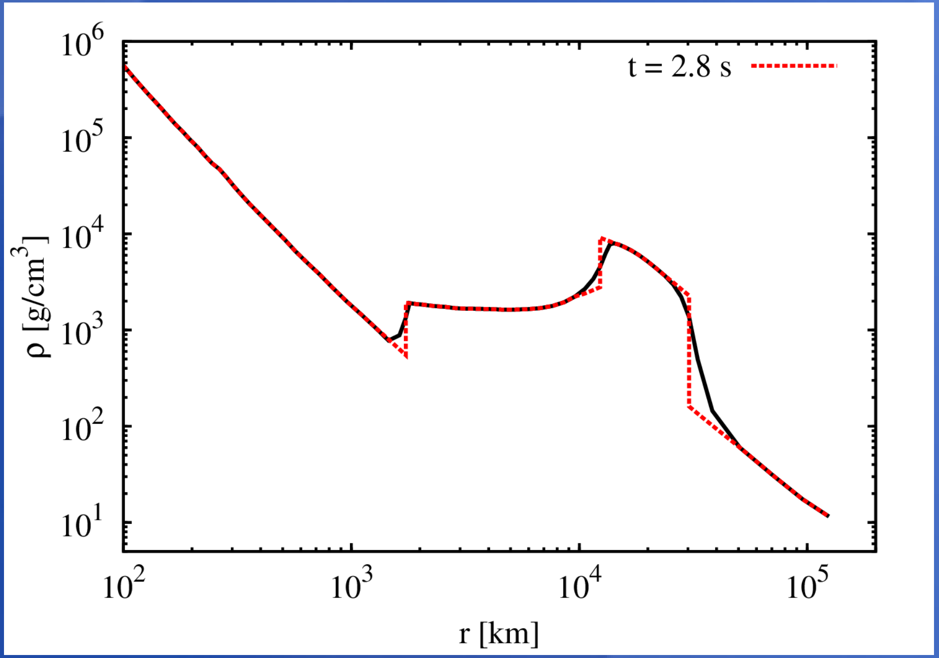
Density profiles

- Ideally multi-D simulations but does not go long enough.
- 1D sim. of 8.8 $M_\odot$, 10.8 $M_\odot$ and 18.0 $M_\odot$ progenitors.
- Provided by Basel group.
- 4.5, 10.7 and 21 s pb duration.
- L and E from same simulations.
- 10.8 $M_\odot$ develops contact discontinuity, forward and reverse shocks.



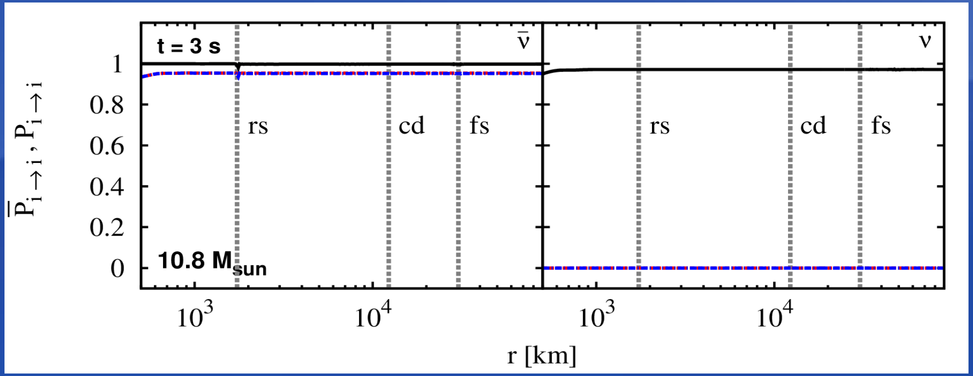
Shock morphology

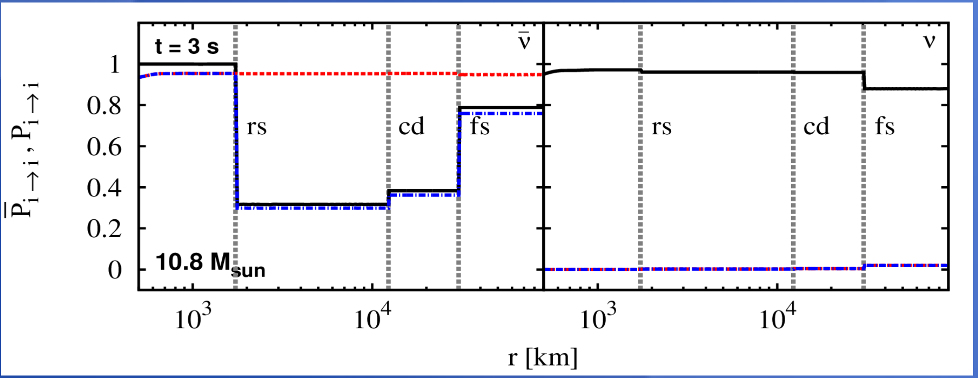
- Numerical soft shocks.
- When θ_{13} is big, only adiabatic transitions happens: $\gamma \gg 1$,
  $\gamma \propto n_e / (dn_e / dr)$
  $P_{jump} = exp(-\gamma\pi/2)$
- Need diabatic at shock.
- Partially steepend by hand.



Steepness of density profiles

20 MeV ν and $\bar{\nu}$, IH





Original profile, black line on previous slide.

Steepened profile, red line on previous slide.

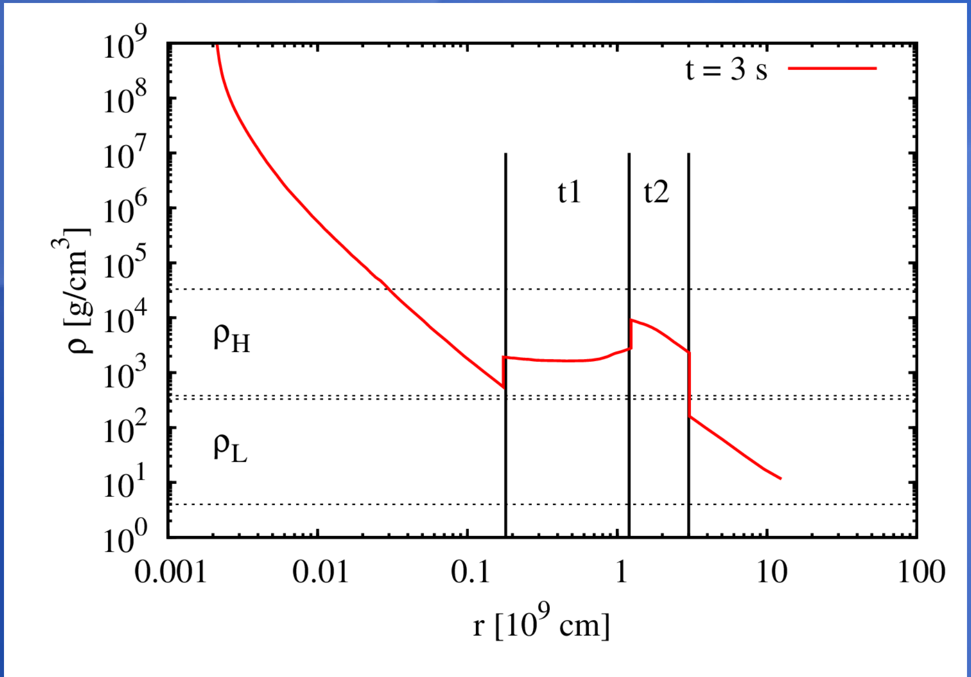
Turbulence

- ρ profiles from 1D simulation.
- Turbulence by hand – 2 areas.
- From Kneller & Volpe (2010), we have the equations for adding turbulence:

$$V(r) = (1 + F(r)) \langle V \rangle (r)$$

- Where *F(r)* is given by:

$$F(r) = \frac{C_\star}{\sqrt{N_k}} \tanh\left(\frac{r - r_r}{\lambda}\right) \tanh\left(\frac{r_s - r}{\lambda}\right) \times \sum_{n=1}^{N_k} \{A_n \cos[k_n(r - r_r)] + B_n \sin[k_n(r - r_r)]\}$$



- $C_* = 0.1, 0.3, 0.5$
- Kolmogorov spectrum

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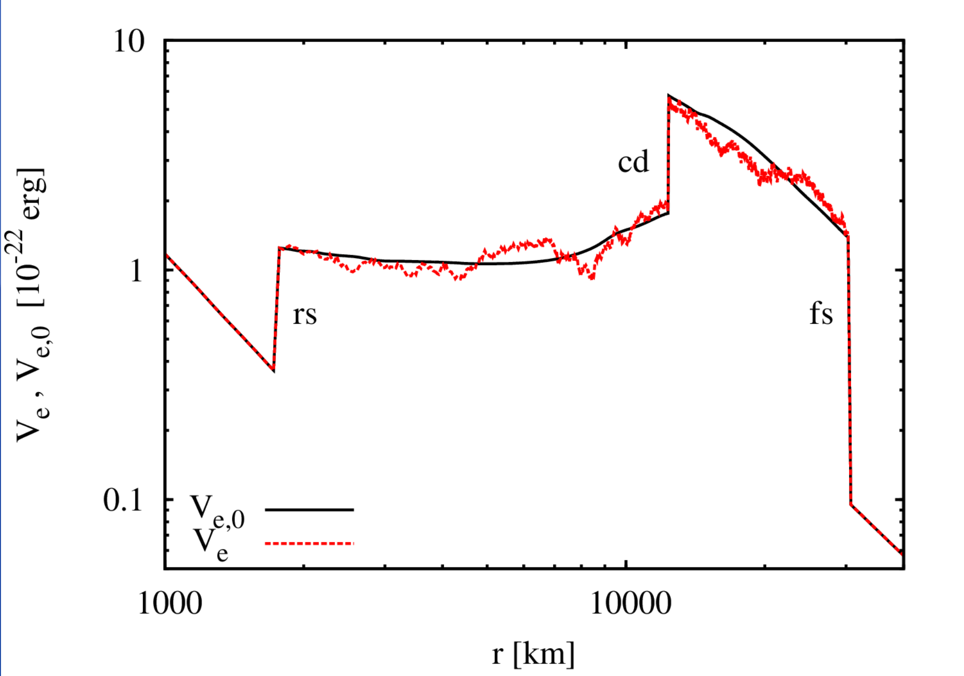
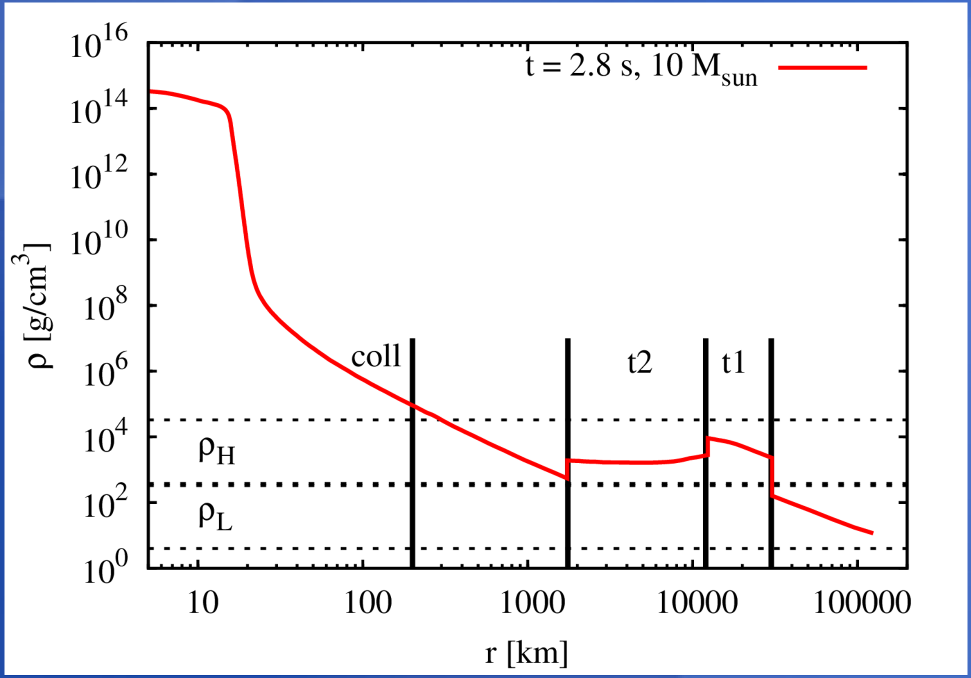


- C_* = 0.1, 0.3, 0.5
- Kolmogorov spectrum

Neutrino propagation

- υ produced at PNS.
- Changes flavor due to:
  - collective effects
  - matter effects
- Matter resonances:
  ρ_H : Δm_{13}^2 and θ_{13}
  ρ_L : Δm_{12}^2 and θ_{12}
- Turbulence changes matter effects.



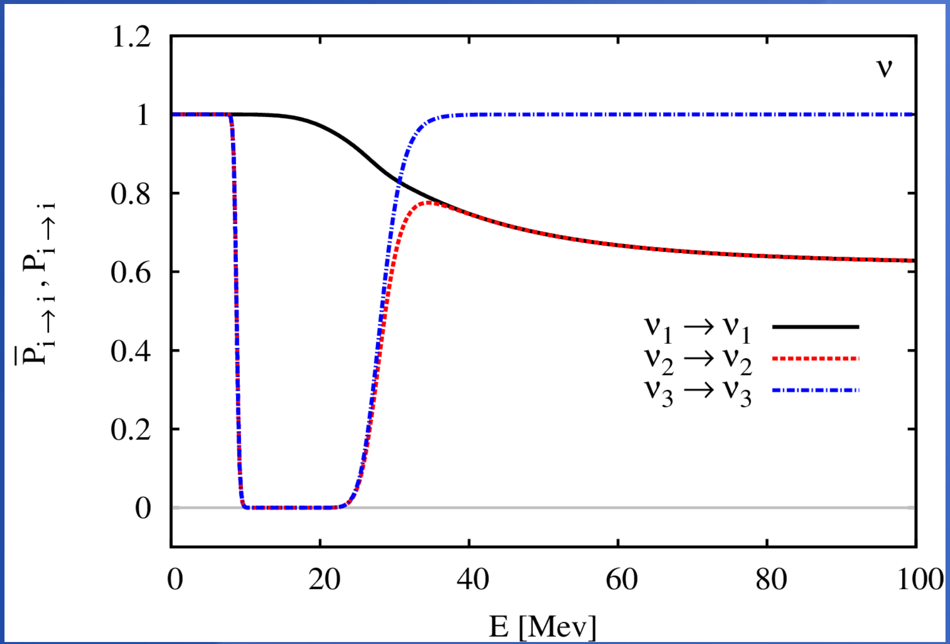
Results

More details in:
T. Lund and J. P. Kneller,
Phys. Rev. D 88, 023008 (2013)

Results

- Results are probabilities for matter states;

$$P_{ij} = P(\upsilon_i \rightarrow \upsilon_j)$$

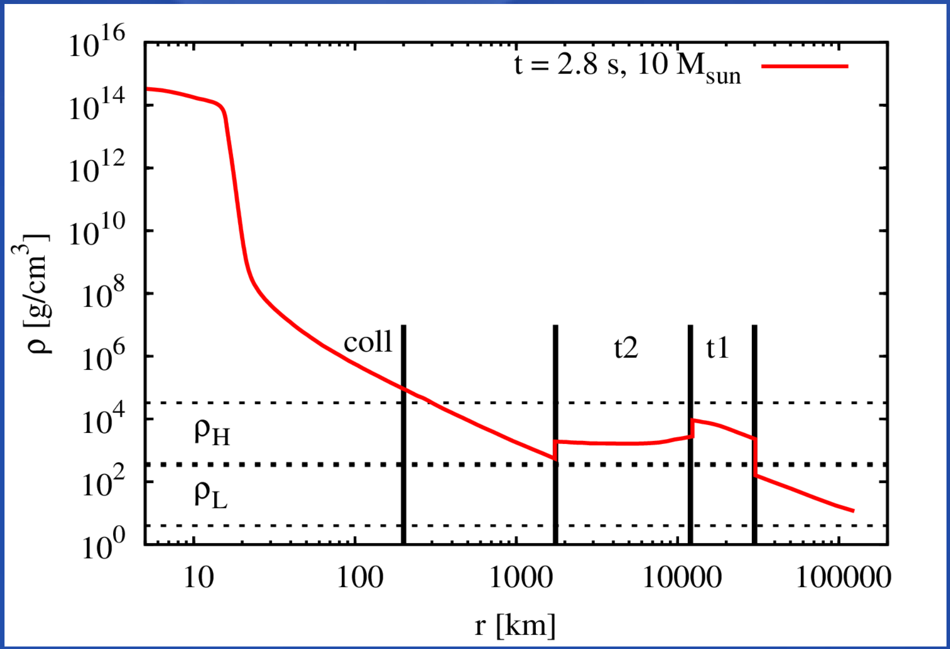


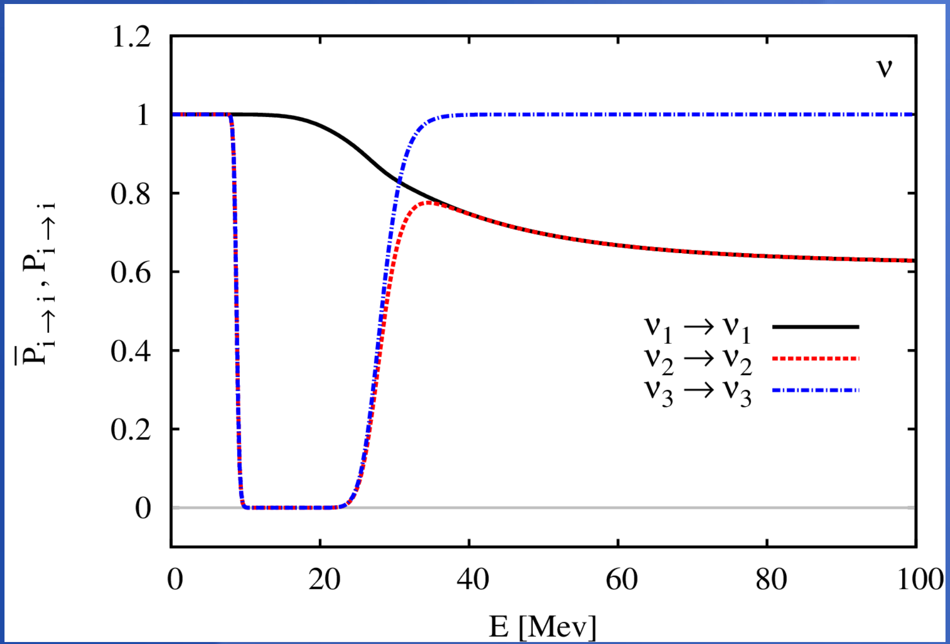
Results

- Collective: 70 - 1000 km
- Matter: 1000 km – end
- Combined: 70 km - end

- Results are probabilities for matter states;

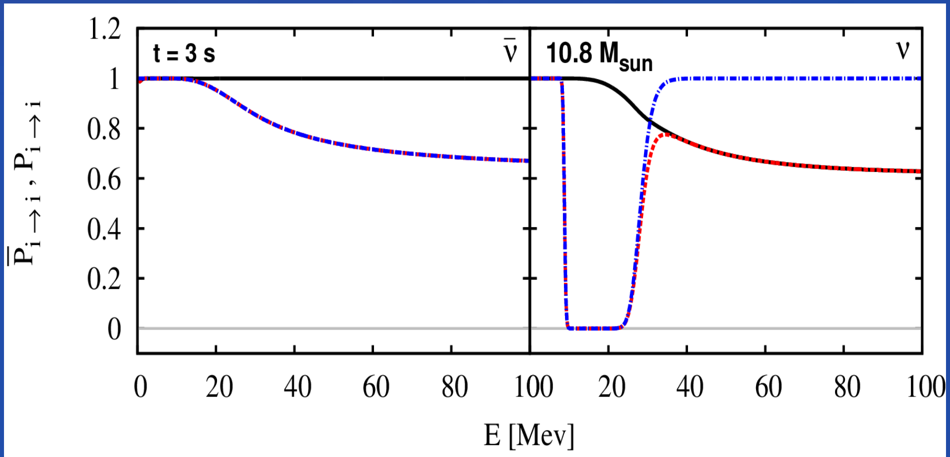
$$P_{ij} = P(\upsilon_i \rightarrow \upsilon_j)$$



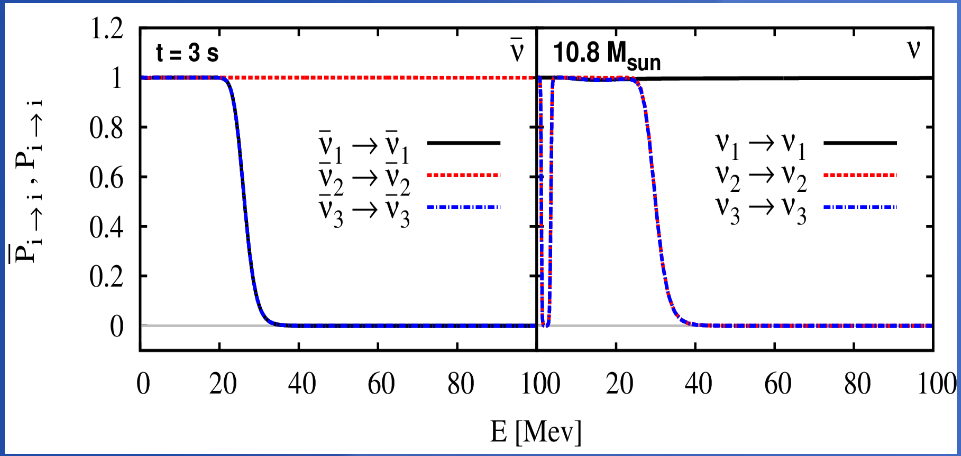


Collective induced features

- Complete conversions for some E.
- Partial conversion in IH $\bar{\nu}$.
- Difference between hierarchies.
- Effect in the NH – for both ν and $\bar{\nu}$.



IH

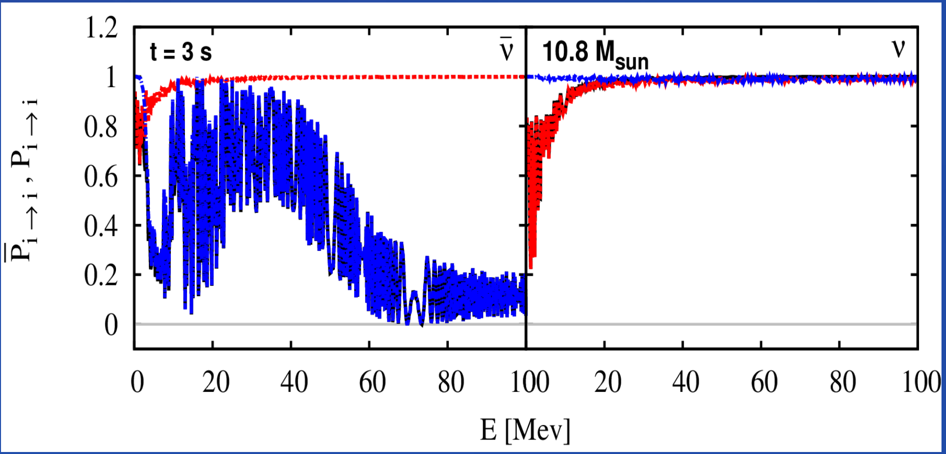


NH

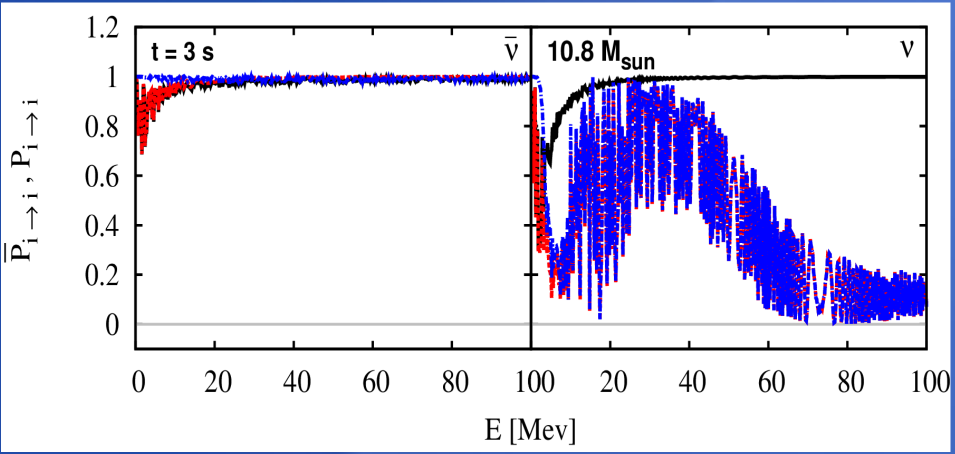
Matter (MSW) induced features

- H resonance clear – for both ν and $\bar{\nu}$.
- L resonance at low E for ν.
- Multiple resonances → phase effect.

NH	IH
H: $\nu_3 \leftrightarrow \nu_2$	H: $\bar{\nu}_3 \leftrightarrow \bar{\nu}_1$
L: $\nu_1 \leftrightarrow \nu_2$	L: $\nu_1 \leftrightarrow \nu_2$

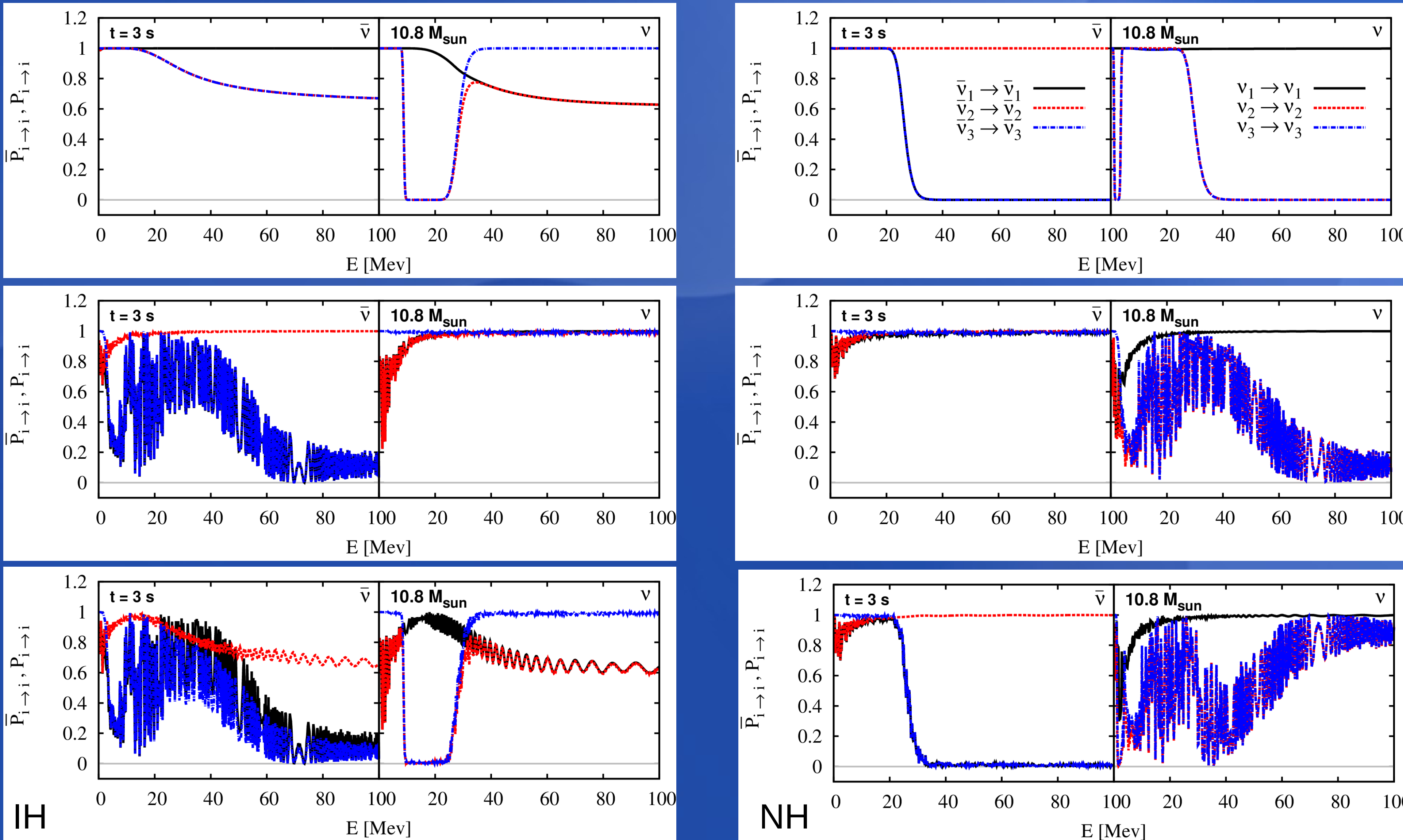


IH



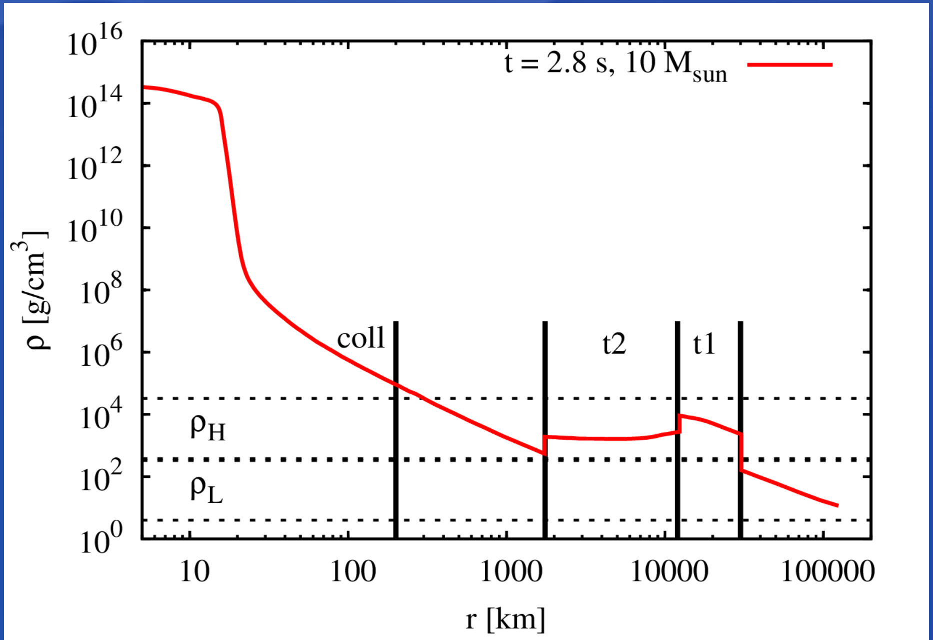
NH

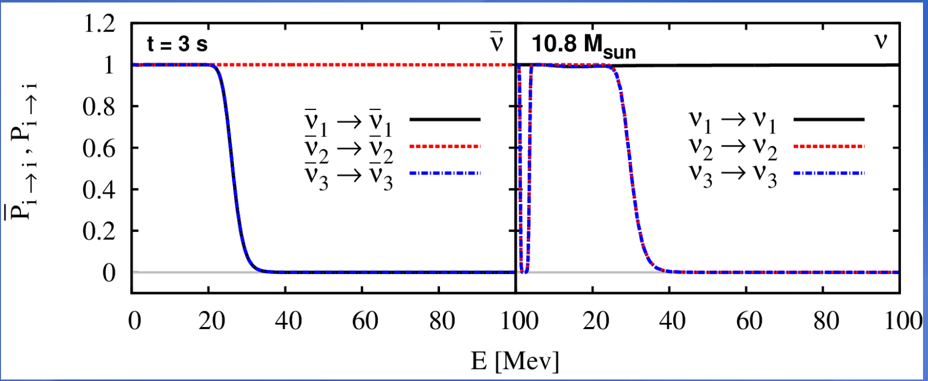
Combined collective and MSW

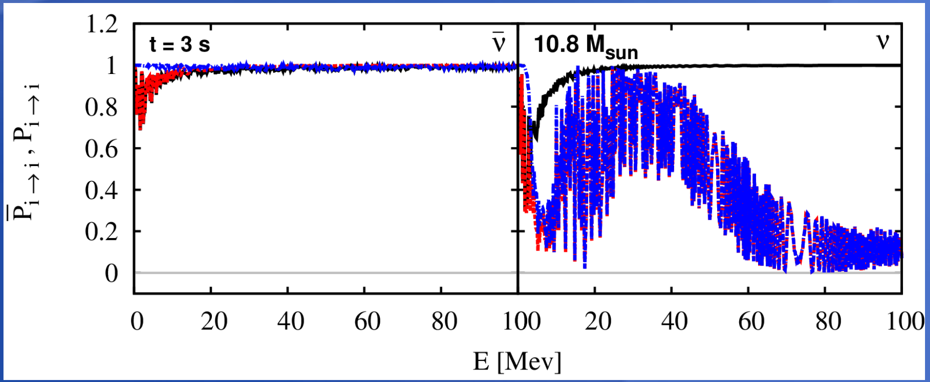


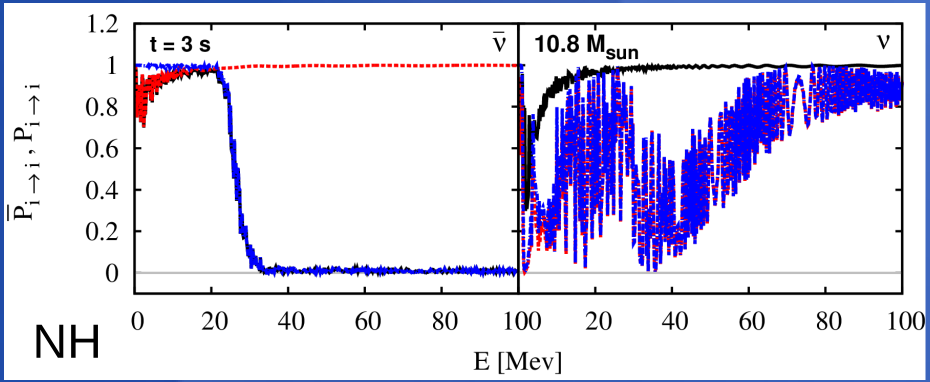
Combined collective and MSW

- Already swapped ν with $E \geq 30$ MeV gets re-swapped by MSW.



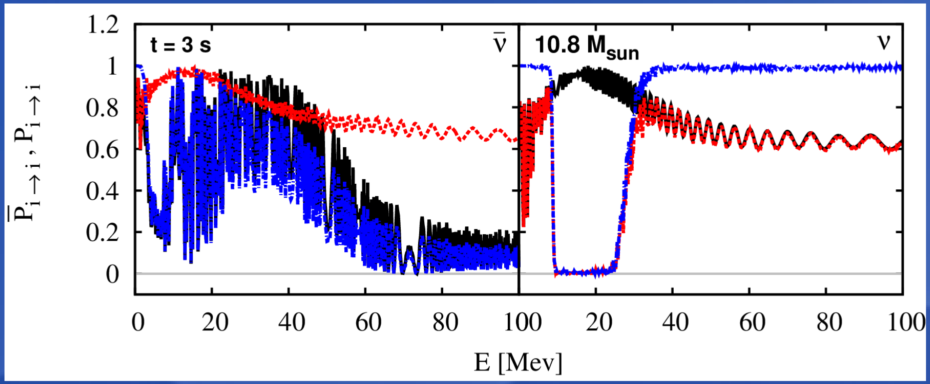






Adding 10% turbulence

IH, no turbulence



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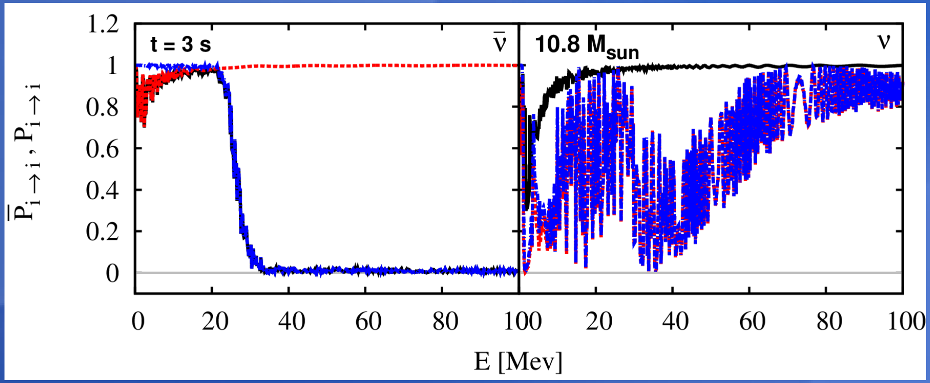
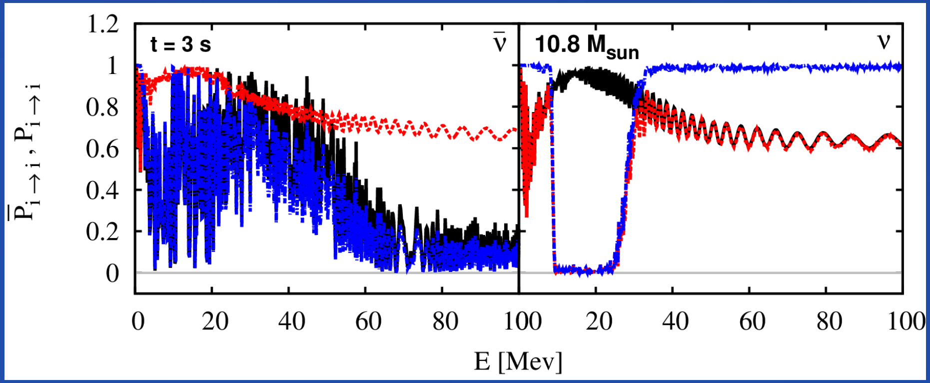


IH, with turbulence



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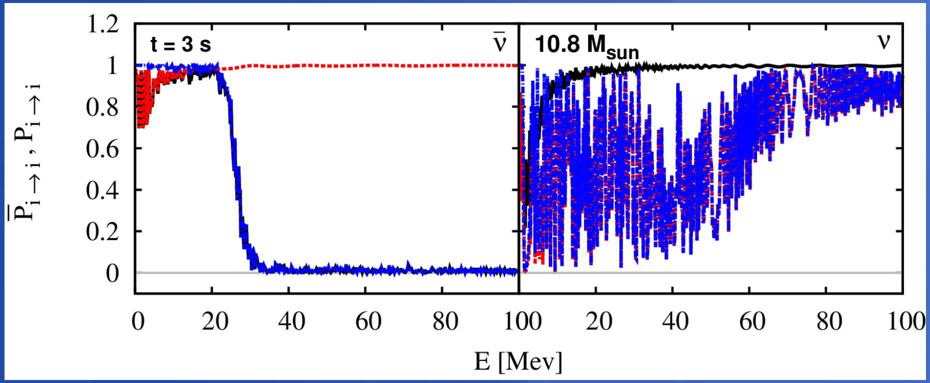

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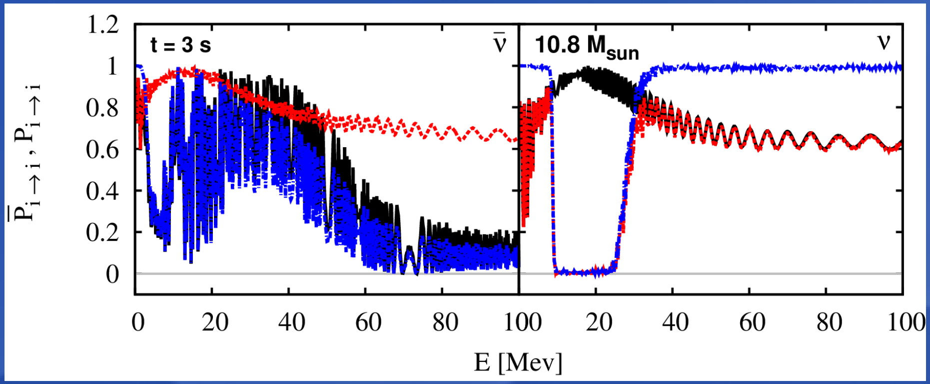

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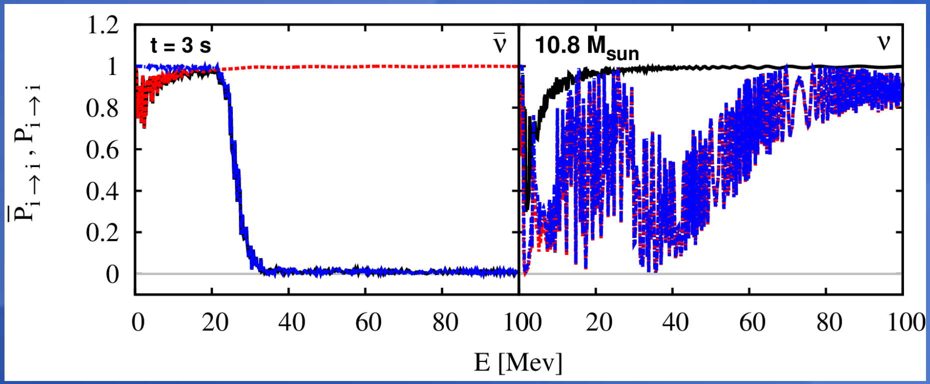

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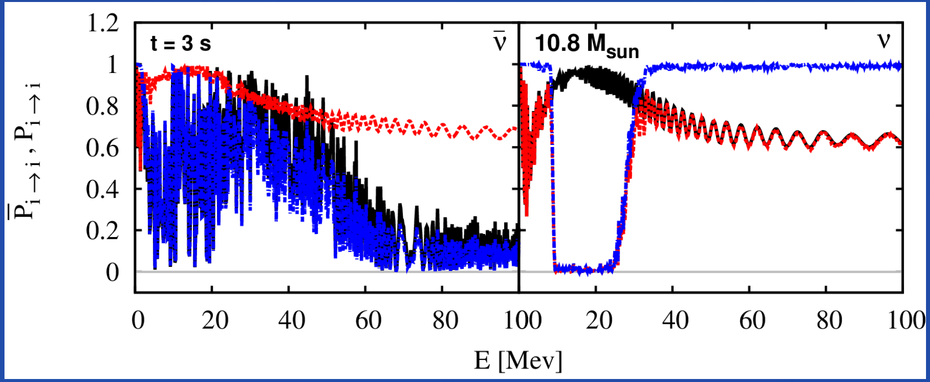
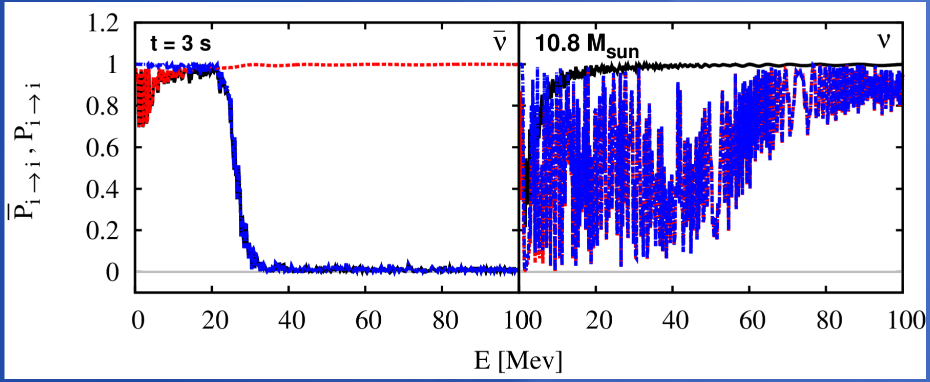


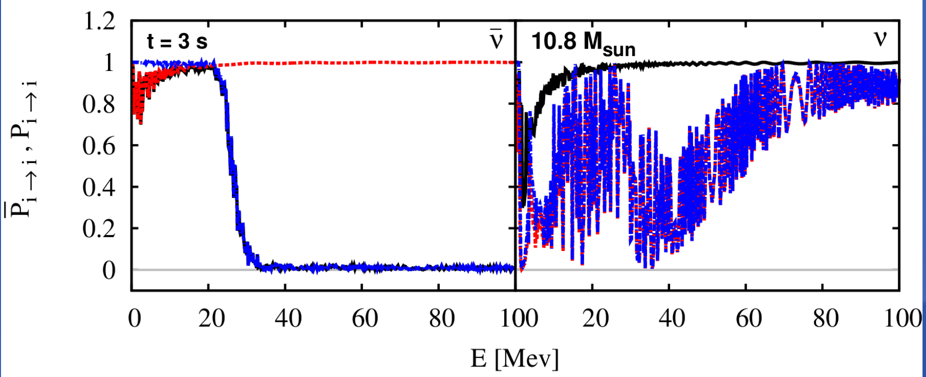
NH, with turbulence



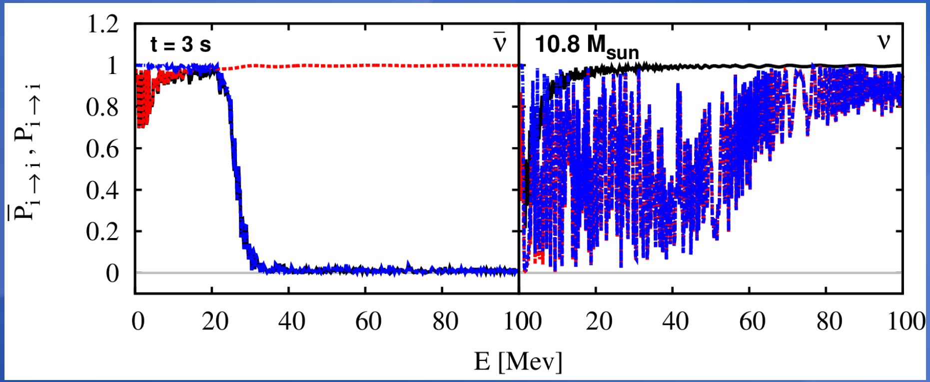
Collective and MSW features survive moderate amounts of turbulence!

Larger turbulence

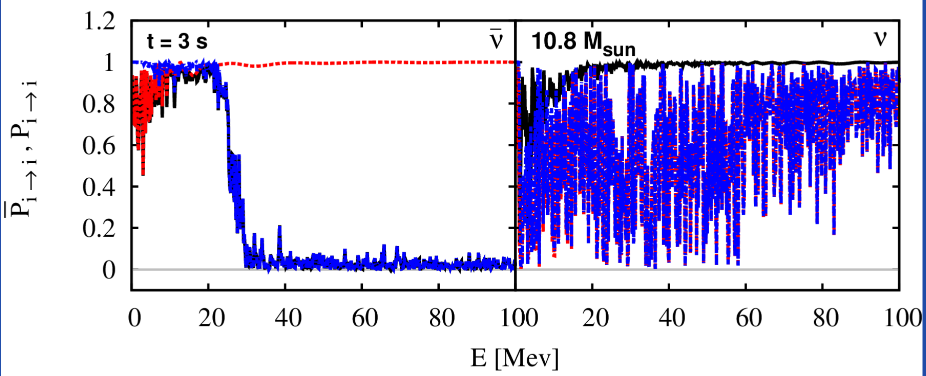
NH, no turbulence



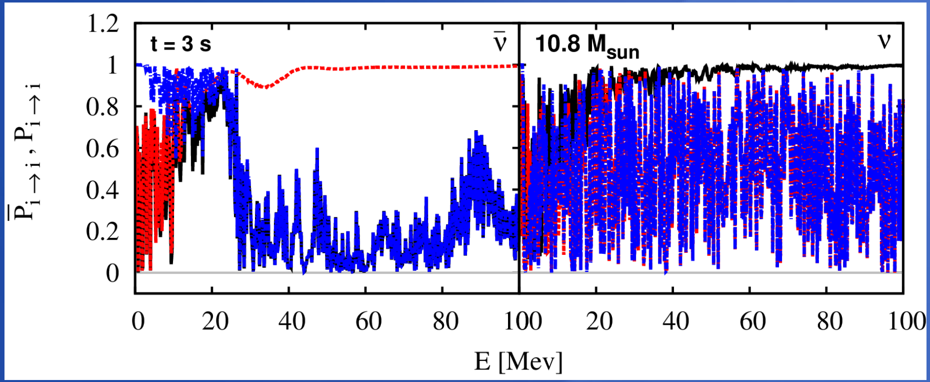
NH, 10% turbulence



NH, 30% turbulence – ”similar” to 10%



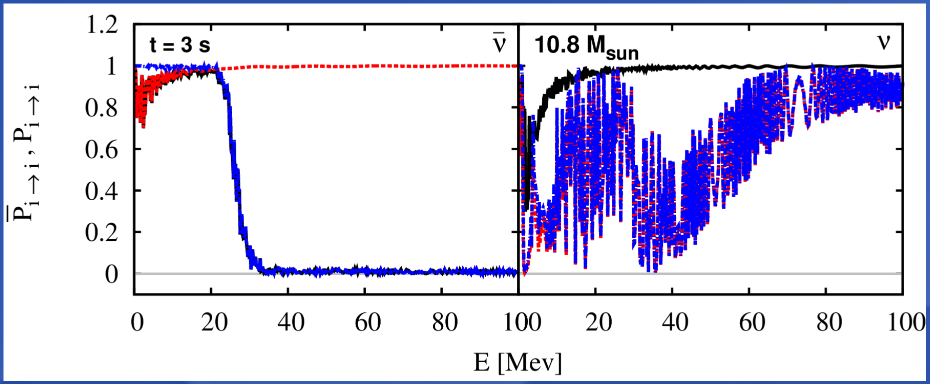
NH, 50% turbulence – a mess



Large amounts of turbulence obscures some collective and MSW features, but also brings new ones to life!

Larger turbulence

NH, no turbulence



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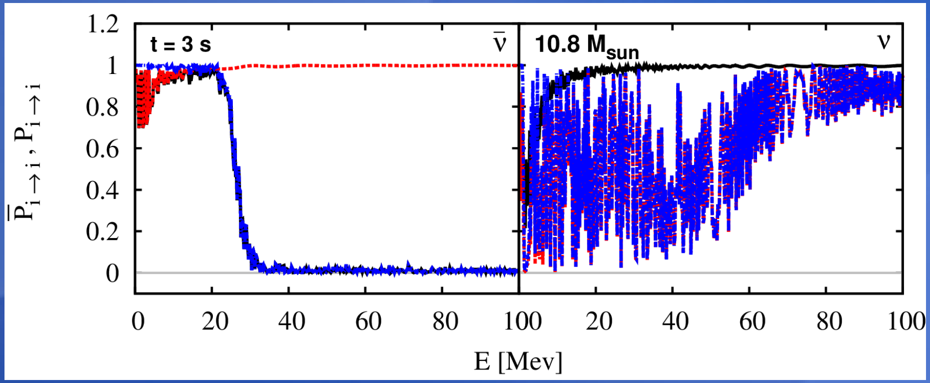
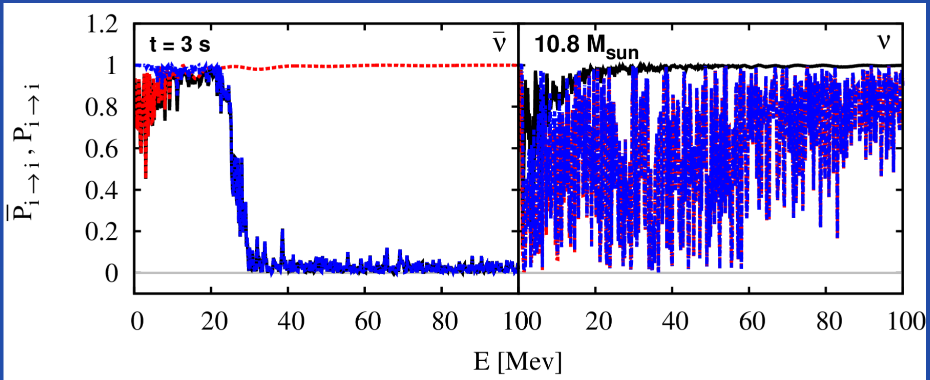
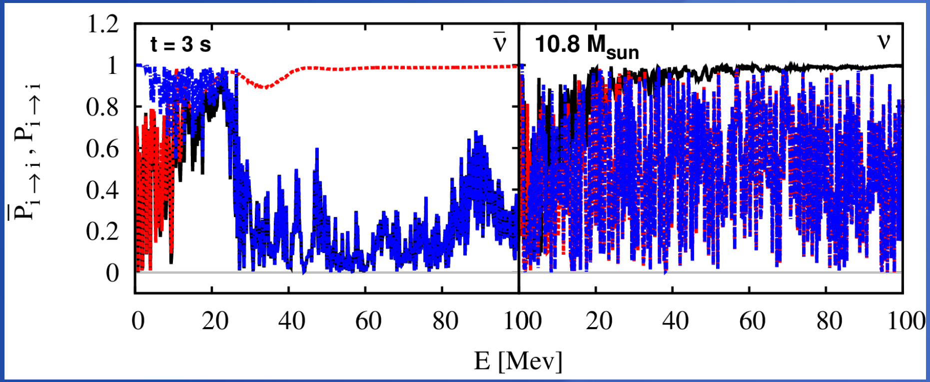


NH, 30% turbulence – "similar" to 10%

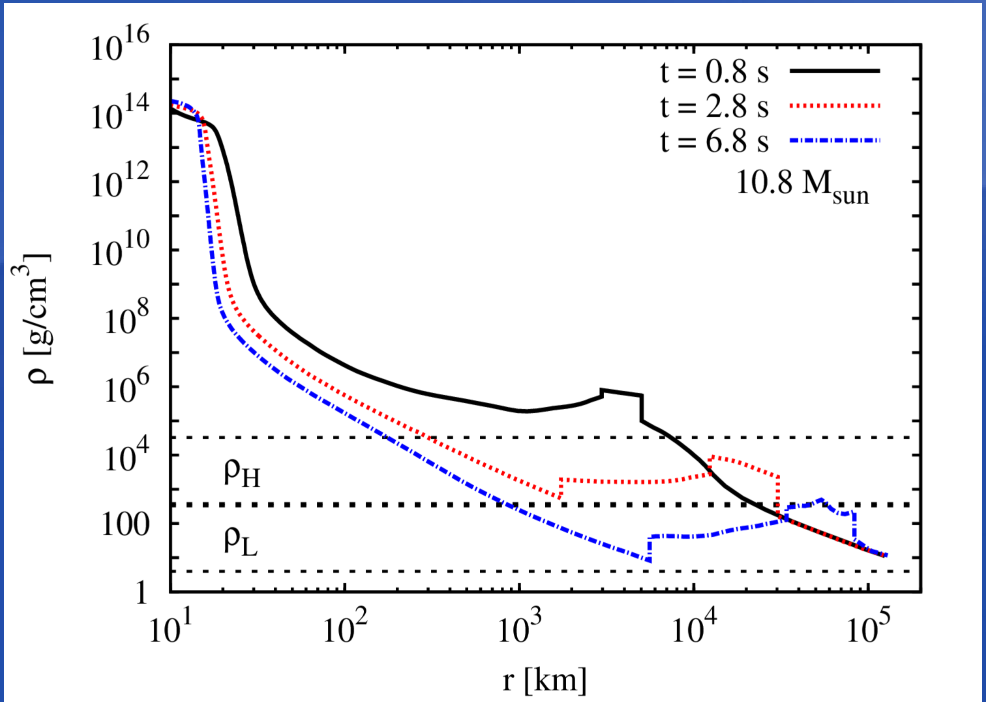


NH, 50% turbulence – a mess



Average $\overline{P}_{11}$ and $\overline{P}_{33}$ above zero at 50%!

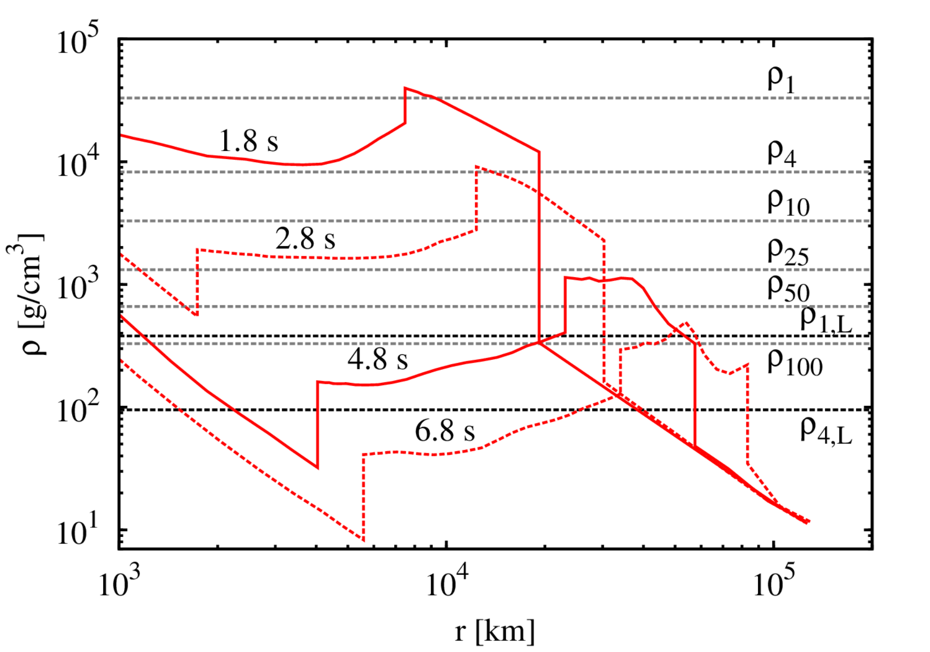
Time evolution of features

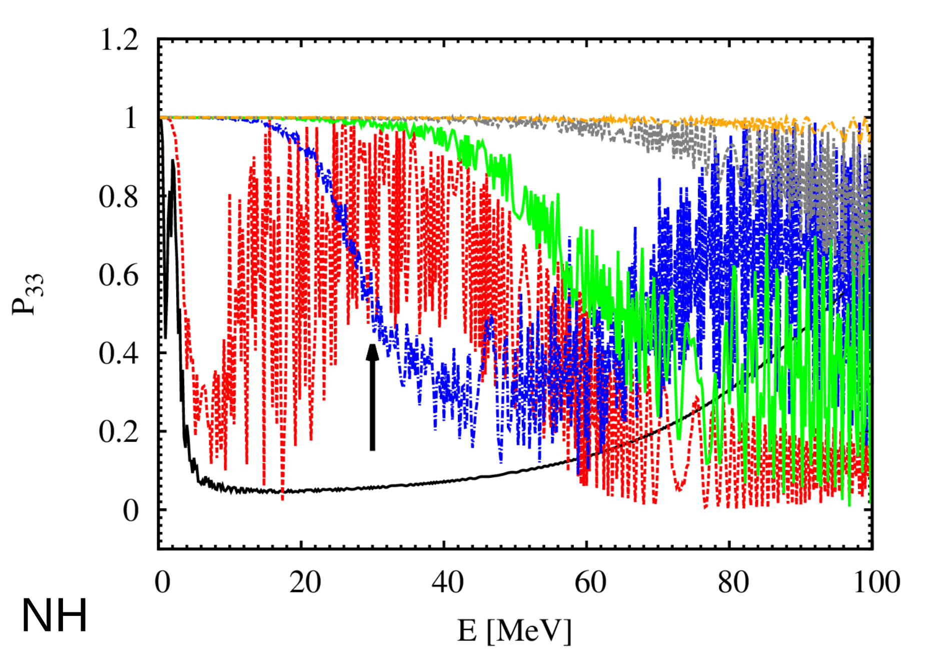


- Results up to now was for one snapshot in time.
- Density profiles evolve:
  - shock moves out in r and thus to lower ρ.
  - reverse shock forms.

Shock wave progression 10 $M_\odot$

At 1.8, 2.8, 4.8, 5.8, 6.8 and 7.8 s

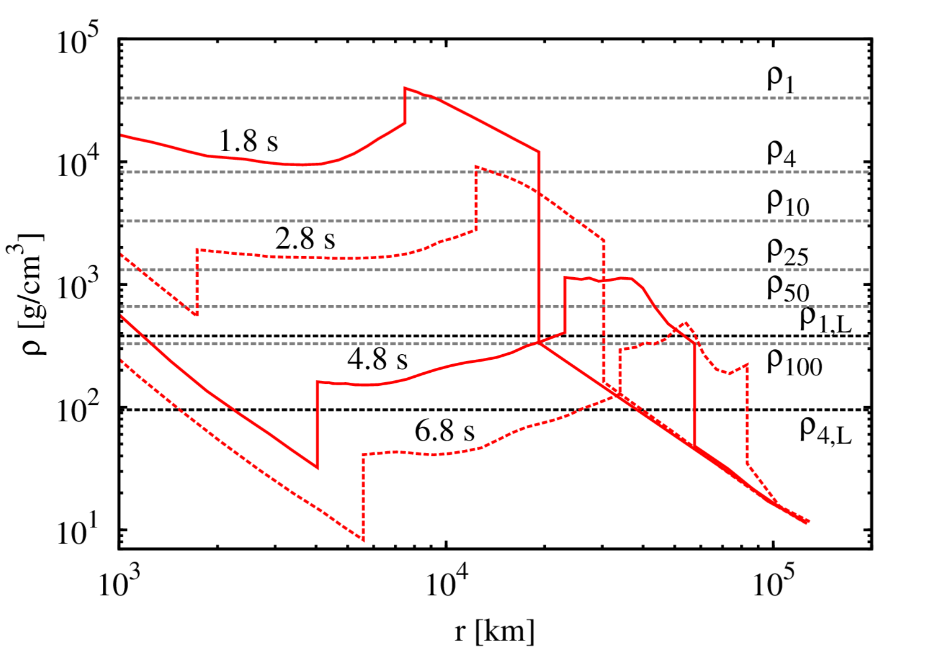


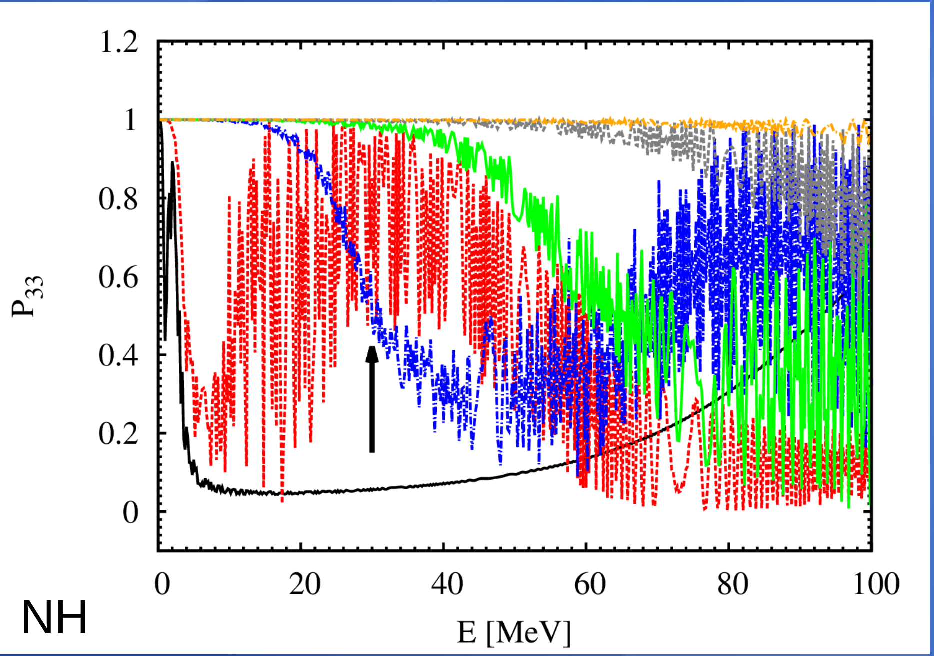


- Following the shock progression to lower densities where higher energy neutrinos have resonance.

Shock wave progression 10 $M_\odot$

At 1.8, 2.8, 4.8, 5.8, 6.8 and 7.8 s

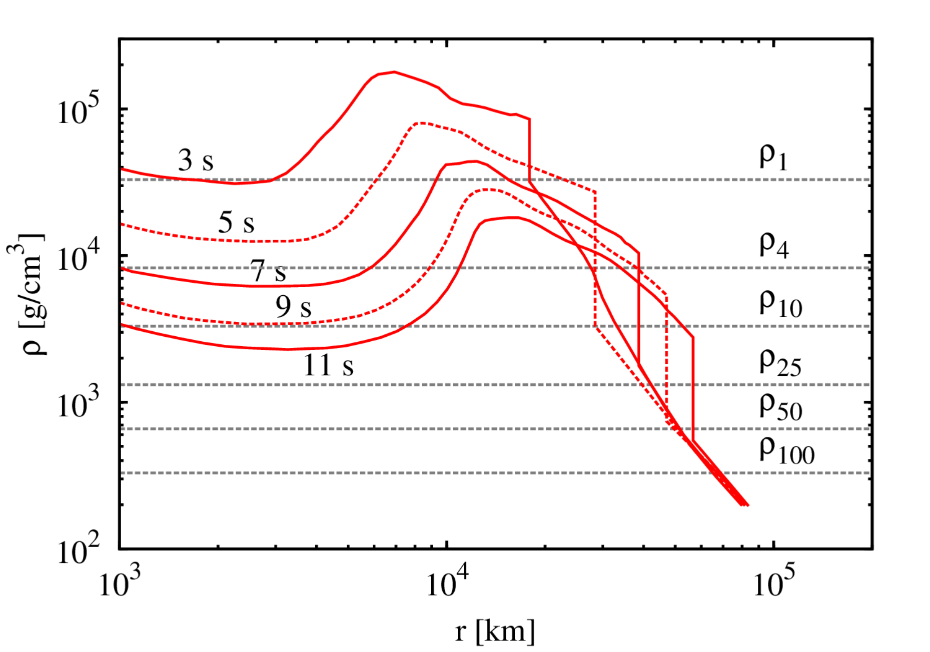


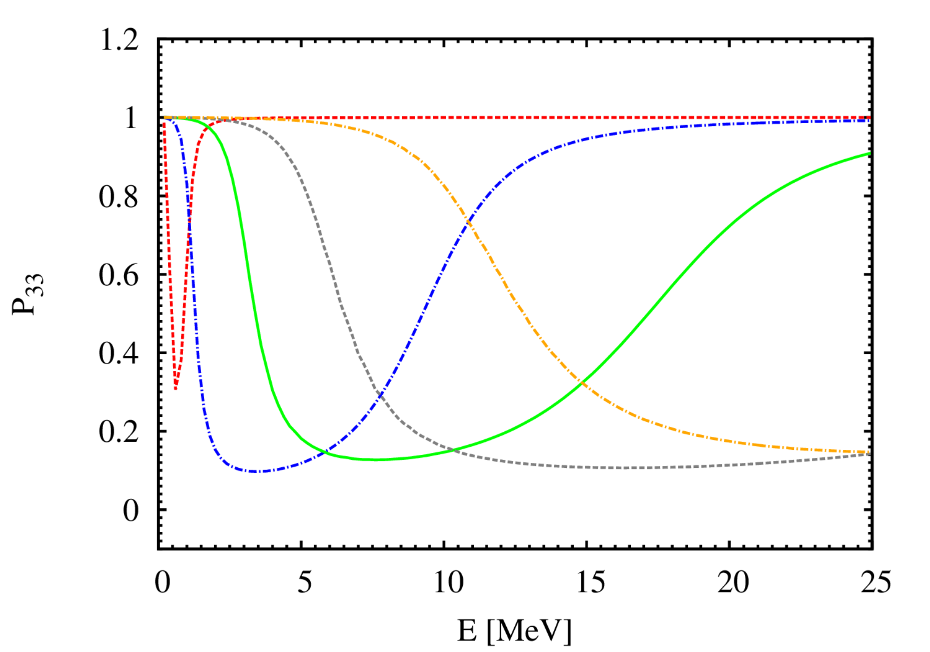


- Following the shock progression to lower densities where higher energy neutrinos have resonance.
- Learn about the progenitor if observed and followed.

Shock wave progression 18 $M_\odot$

At 3, 5, 7, 9 and 11 s

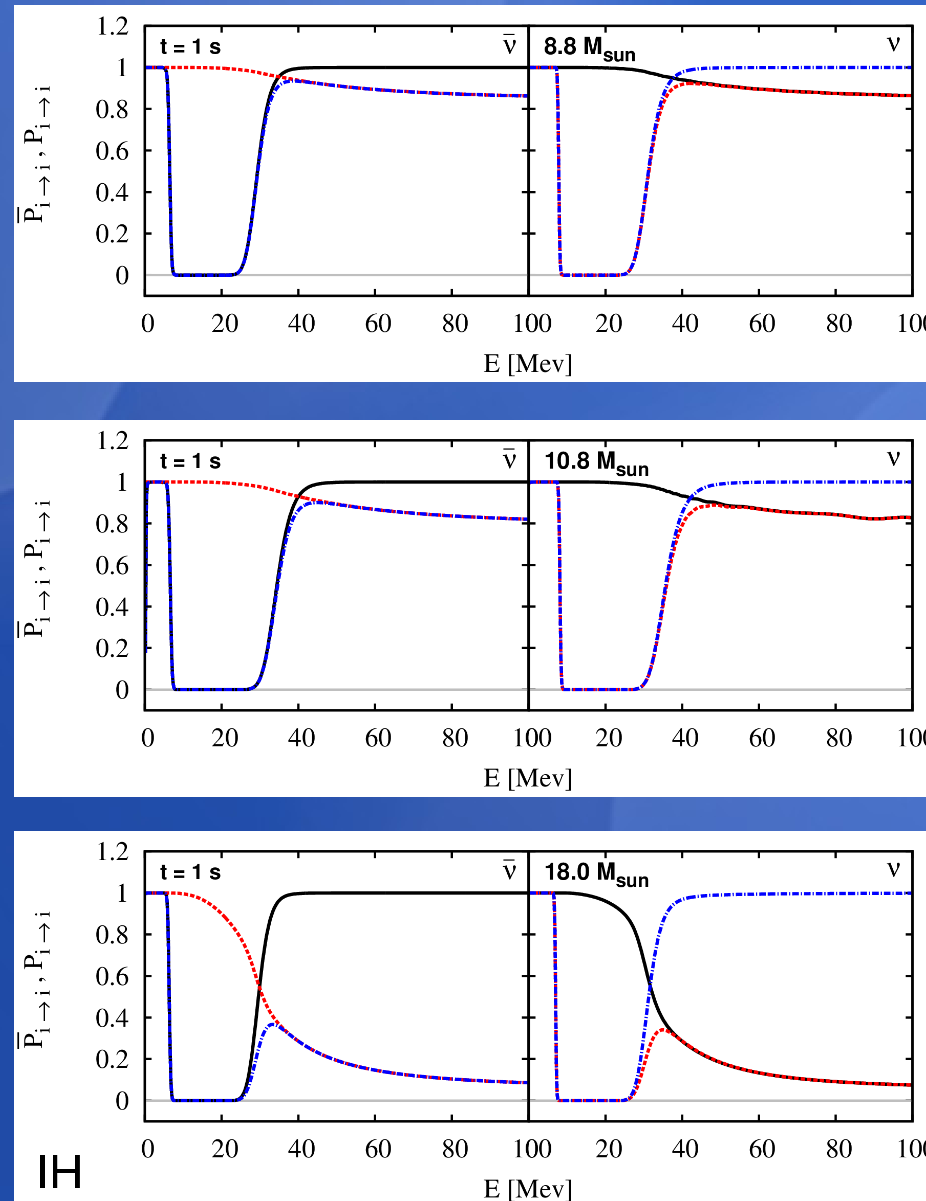




- Cleaner for the 18 $M_\odot$ progenitor – no phase effects.
- More extended envelope thus less change in energy of affected neutrino.

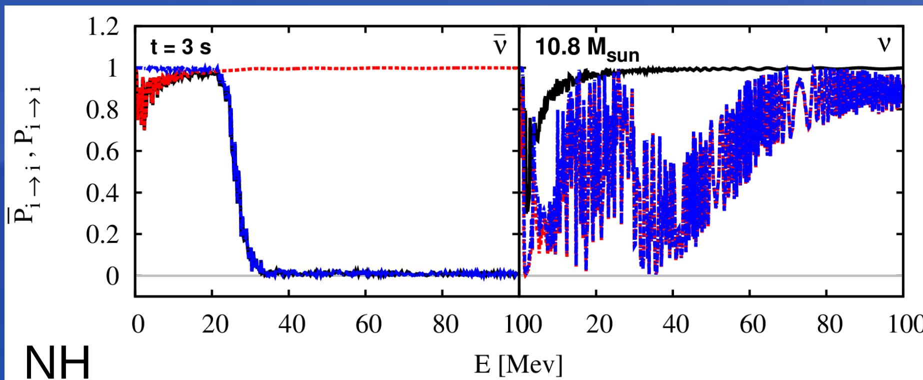
Similarities across progenitors

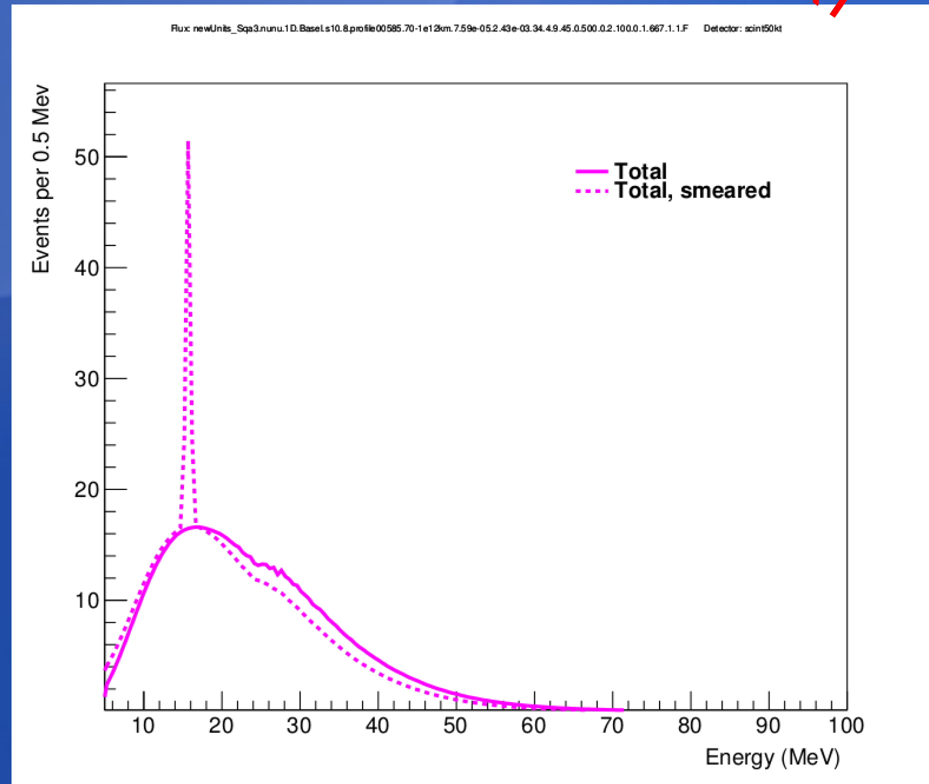
- Masses of 8.8 $M_\odot$, 10.8 $M_\odot$ and 18.0 $M_\odot$.
- Dominated by collective effects at 1 sec.
- Similarity of L and E.
- Collective features are robust.
- 8.8 $M_\odot$ and 10.8 $M_\odot$ have crossings at different E.



Observability

PRELIMINARY





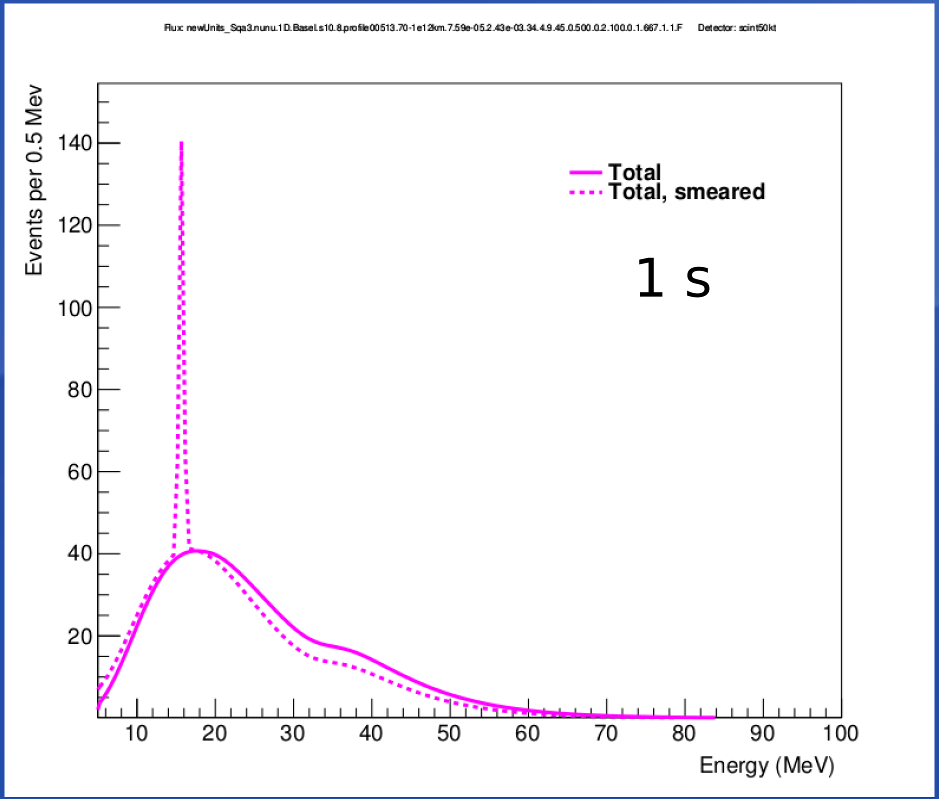
- SNOwGLoBES; scint 50 kt

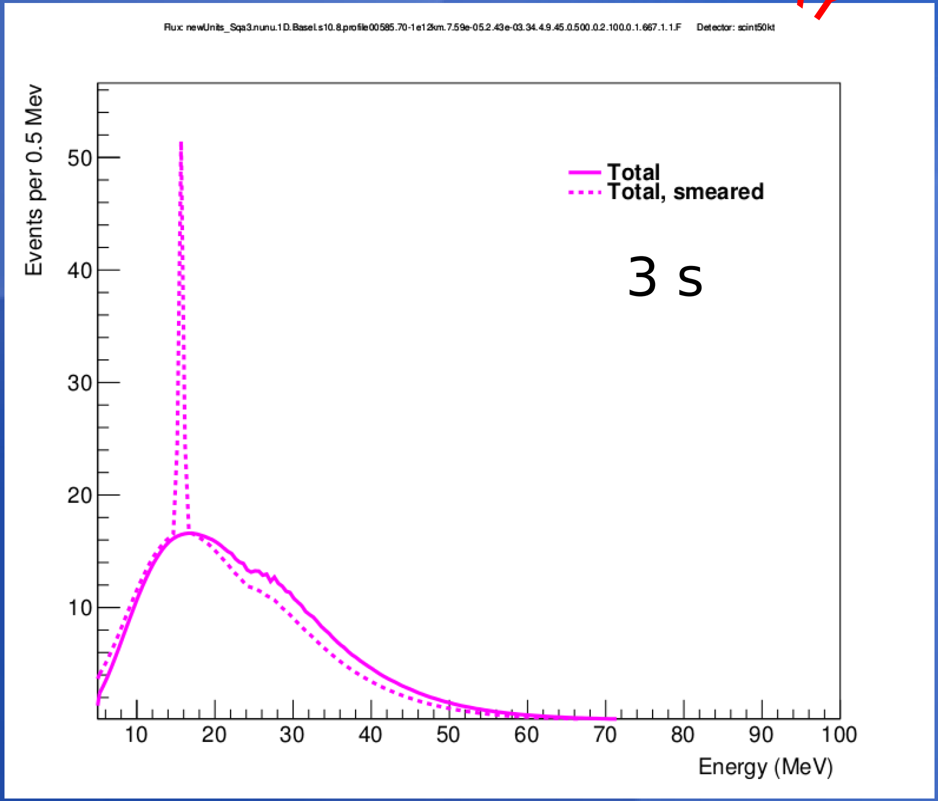
  Caveat: Assumes constant flux over 1 sec.

  Work in progress.

Observability

PRELIMINARY





- SNOwGLoBES; scint 50 kt

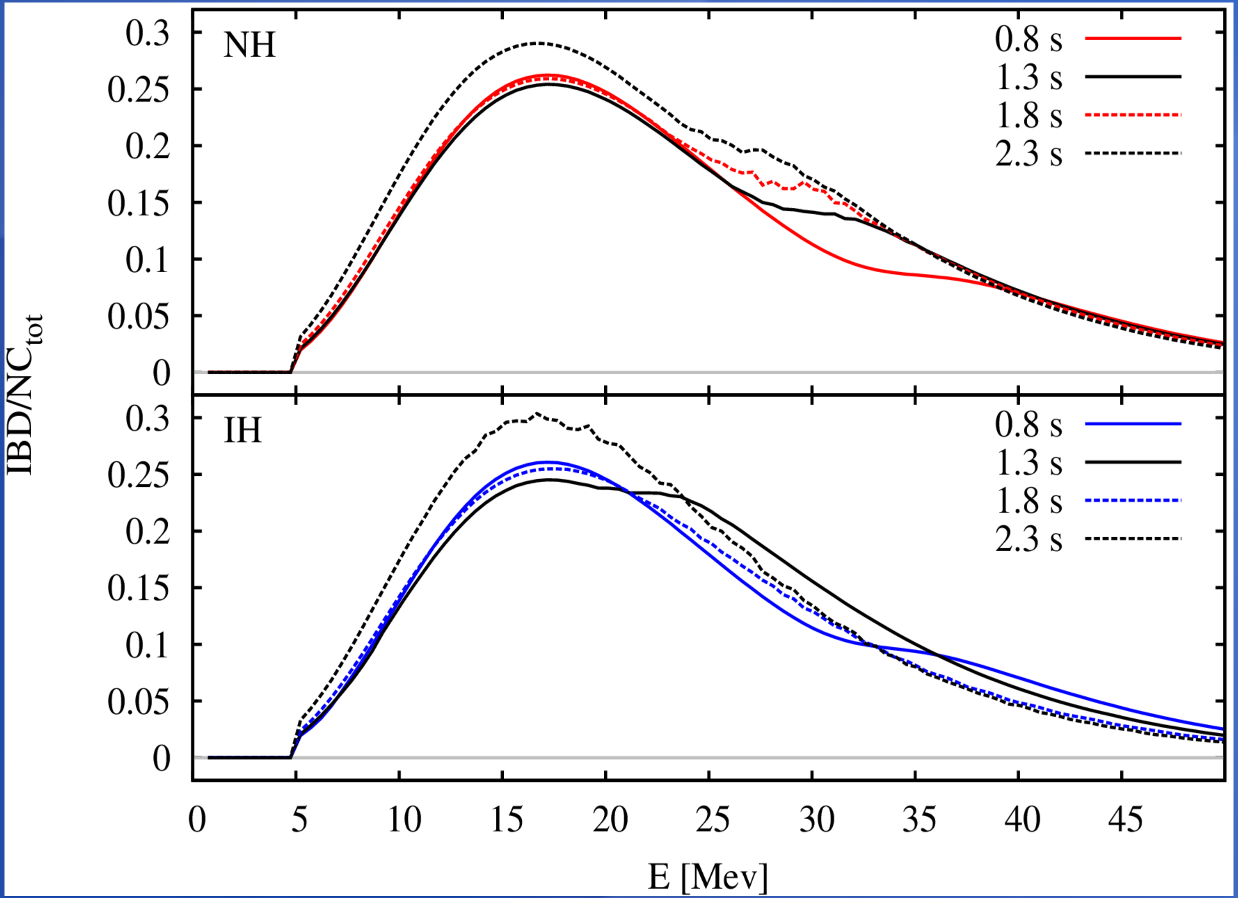
  Caveat: Assumes constant flux over 1 sec.

  Work in progress.

Time evolution

PRELIMINARY

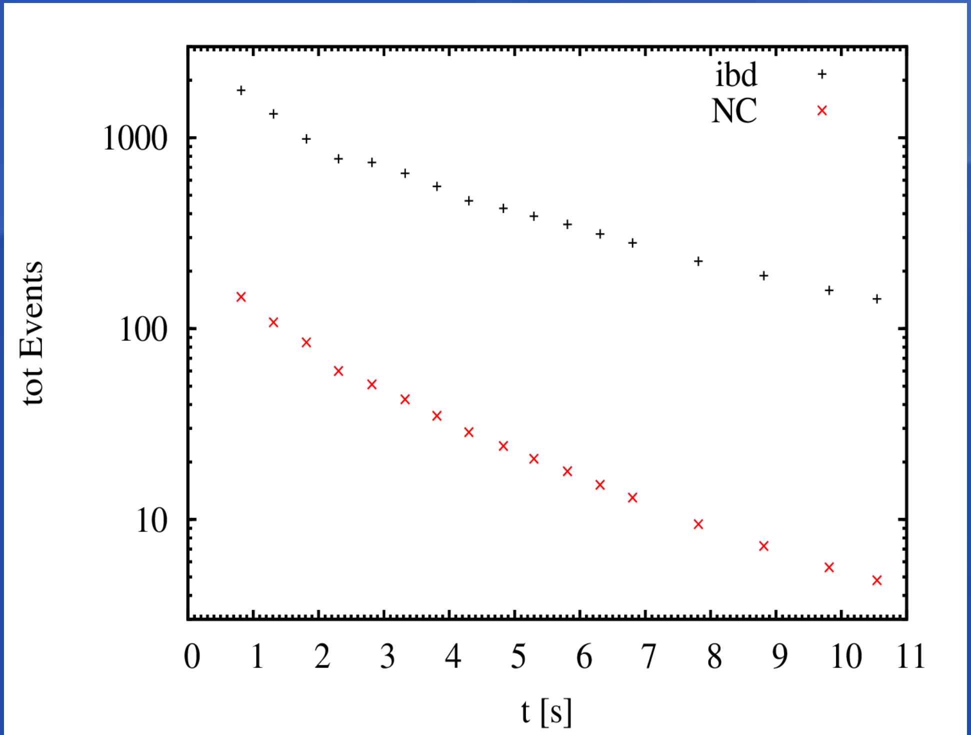
- Movement of collective split.
- Brief shock wave feature.
- Hierarchy differences.

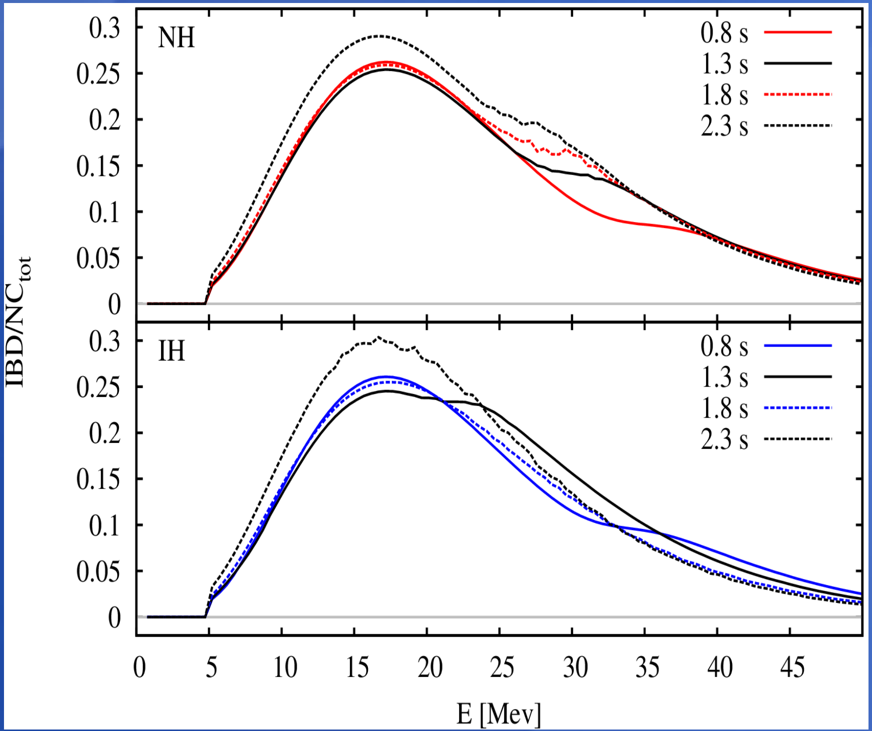


[Work in progress in collaboration with Tara J. Aida]

Time evolution

PRELIMINARY

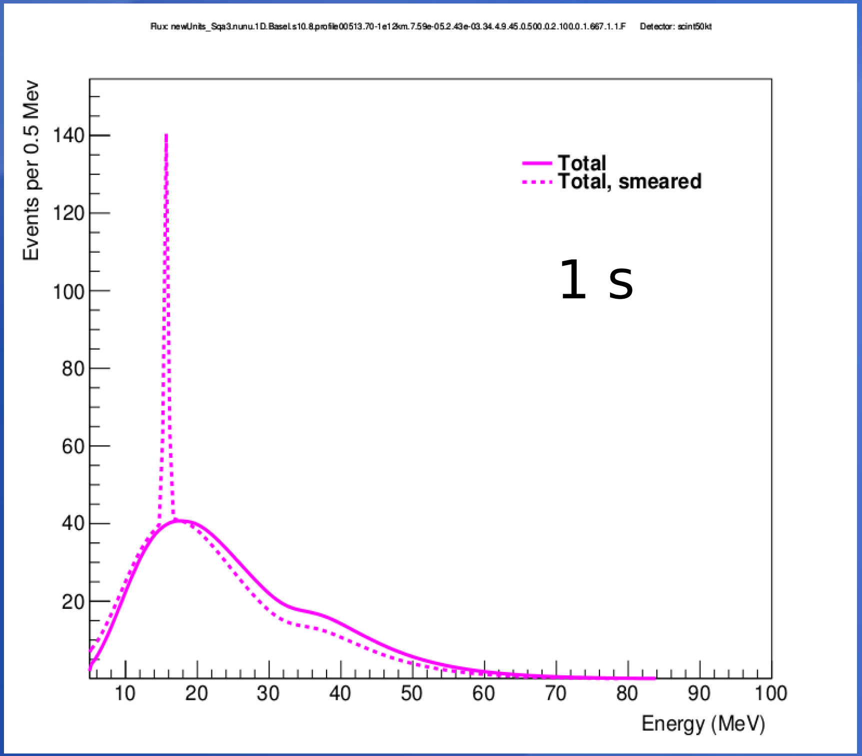




[Work in progress in collaboration with Tara J. Aida]

Lessons from late time signals

- Robust collective features in matter basis, and visible in flux spectra.
- Features of collective and MSW effects survive up to moderate turbulence.
- Turbulence makes things more complex.
- Follow shock wave.

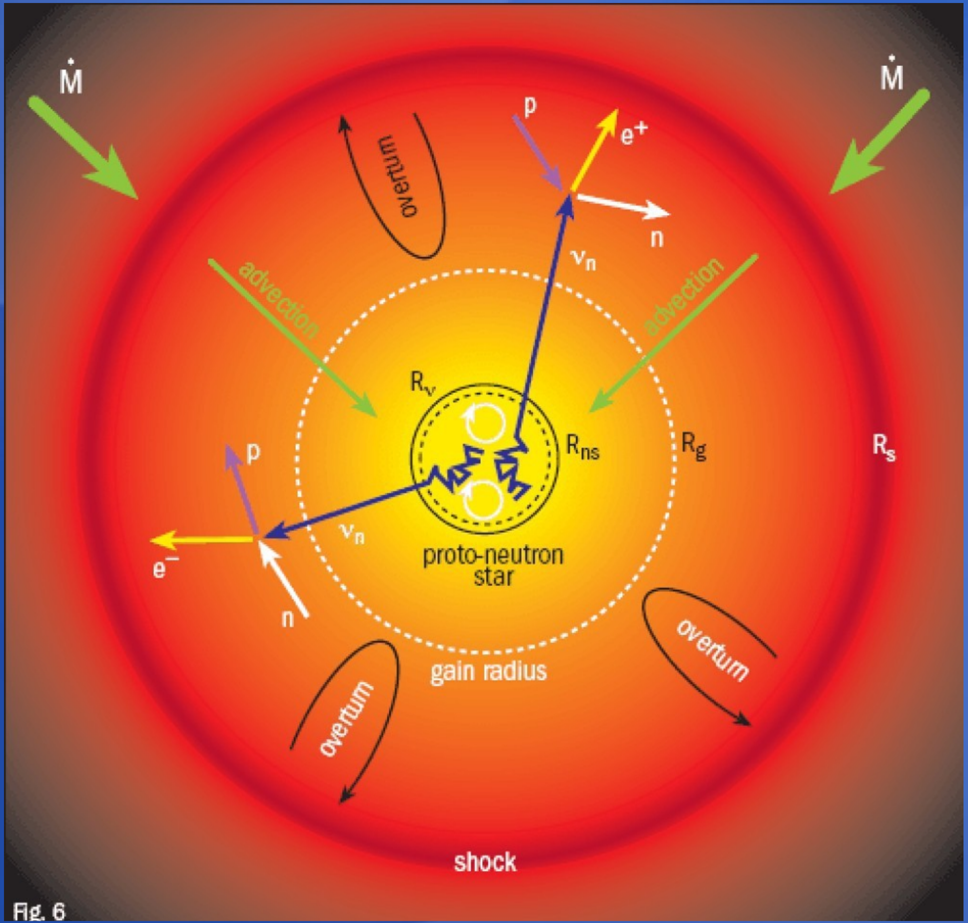


Early time ν observations – signatures of the SASI explosion mechanism

In collaboration with:
H.-Th. Janka, G. Raffelt, A. Wongwathanarat, A. Marek, C. Lunardini and E. Müller

Shock revival

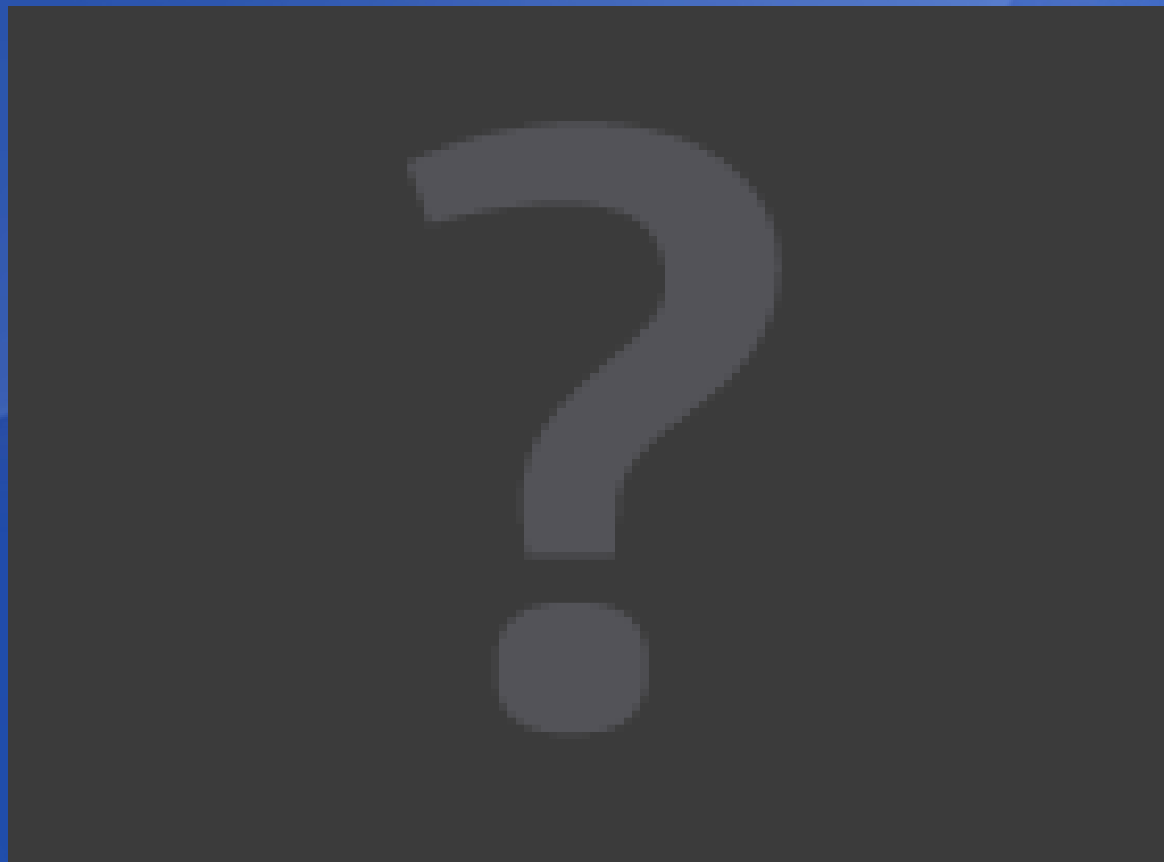
- Outward movement of shock stalls due to energy losses.
- Neutrino heating.
- Aided by SASI – Standing Accretion Shock Instability – increasing gain region.
- Pertubation of shock front decomposed in spherical harmonics.



[Janka et al., 2011]

ccSN SASI

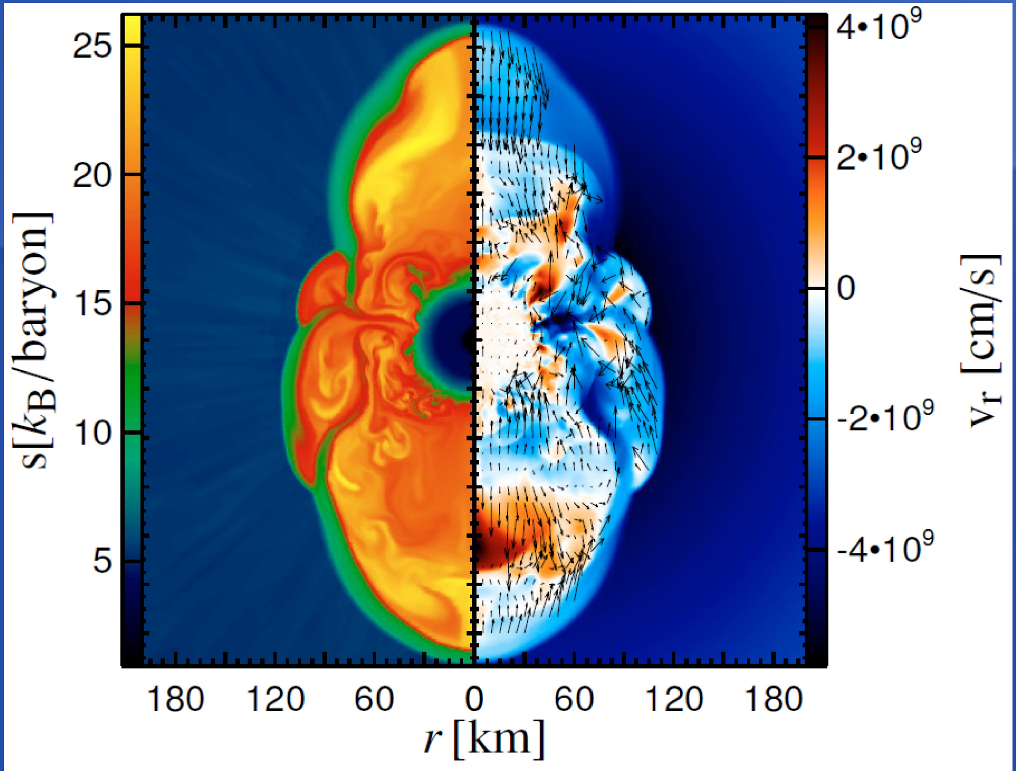
[R.Buras, A.Marek, H.Th.Janka]



2D simulation of a 11.8 M_{sun} progenitor.

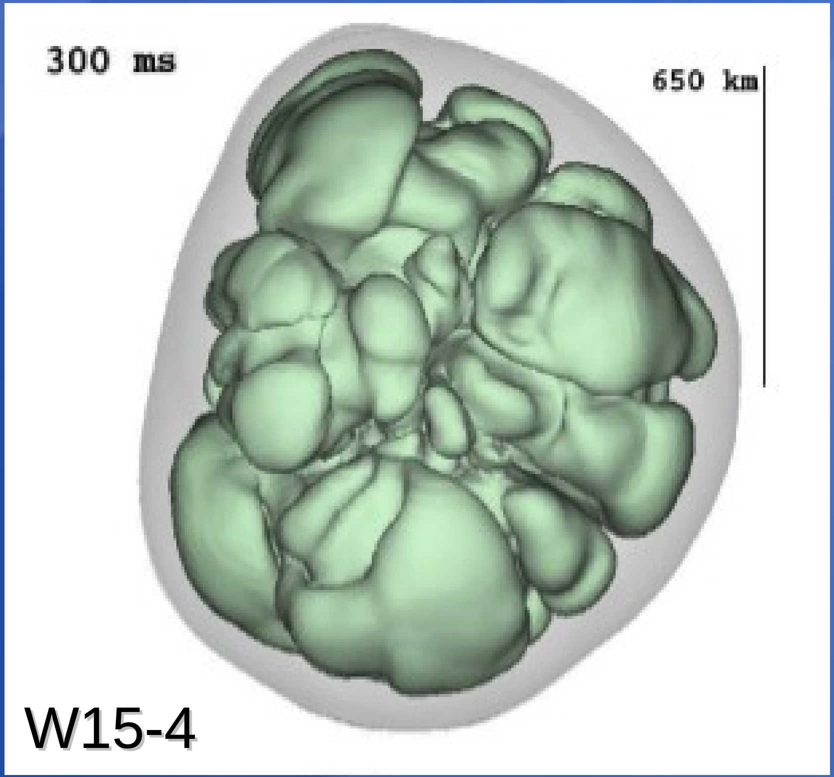
SASI in 2D and 3D

2D non-rotating 15 M_{sun}



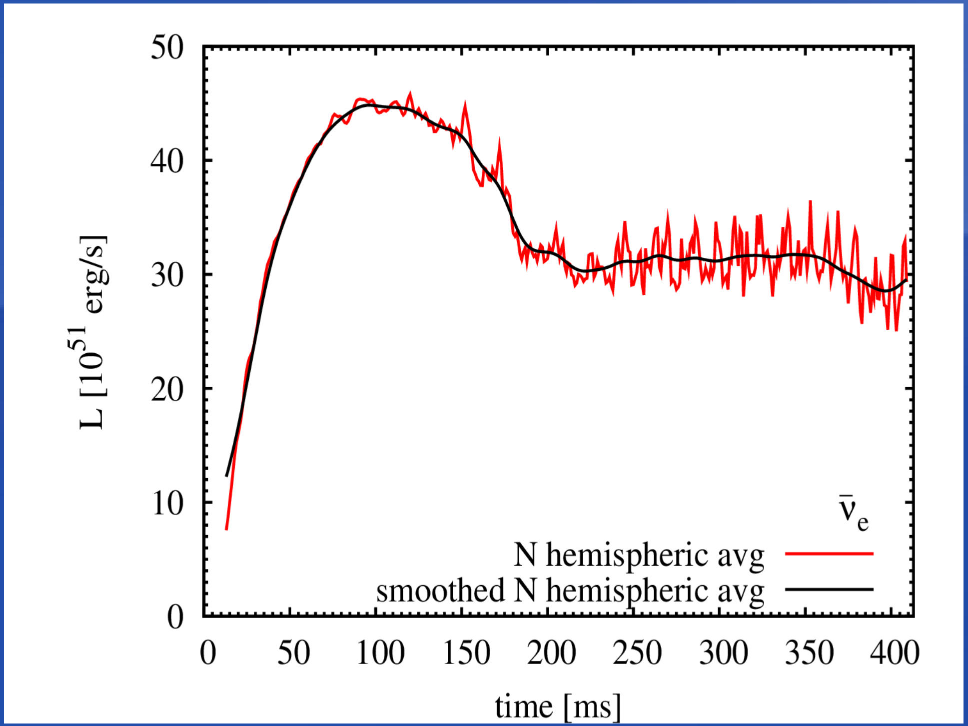
[A. Marek, H.-Th. Janka & E. Müller, 2009]

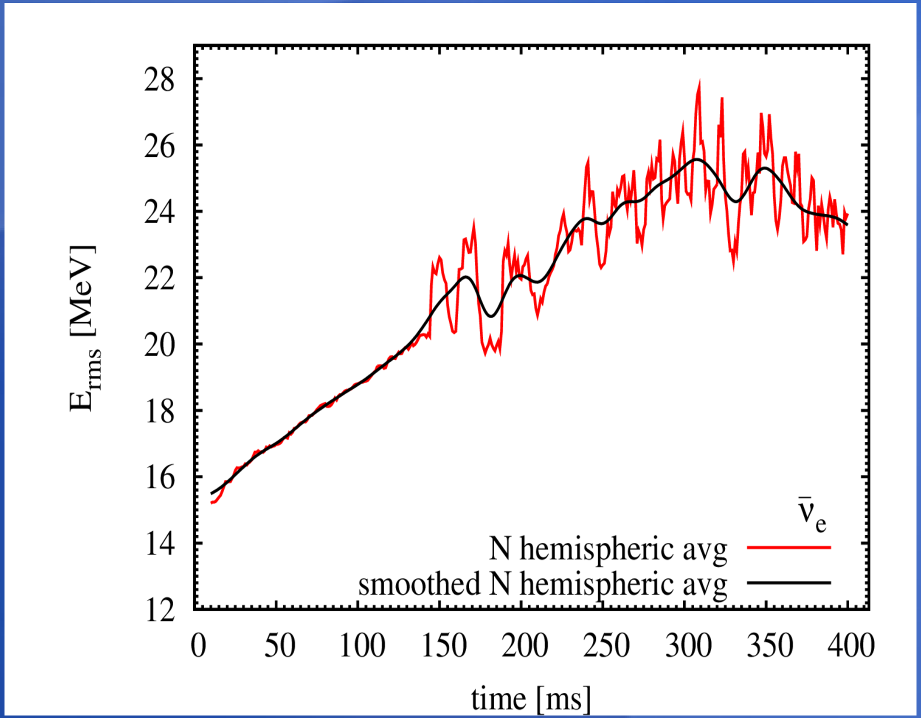
3D non-rotating 15 M_{sun}



[E. Müller, H.-Th. Janka & A. Wongwathanarat, 2011]

Effects of SASI





[Lund et al., 2010]

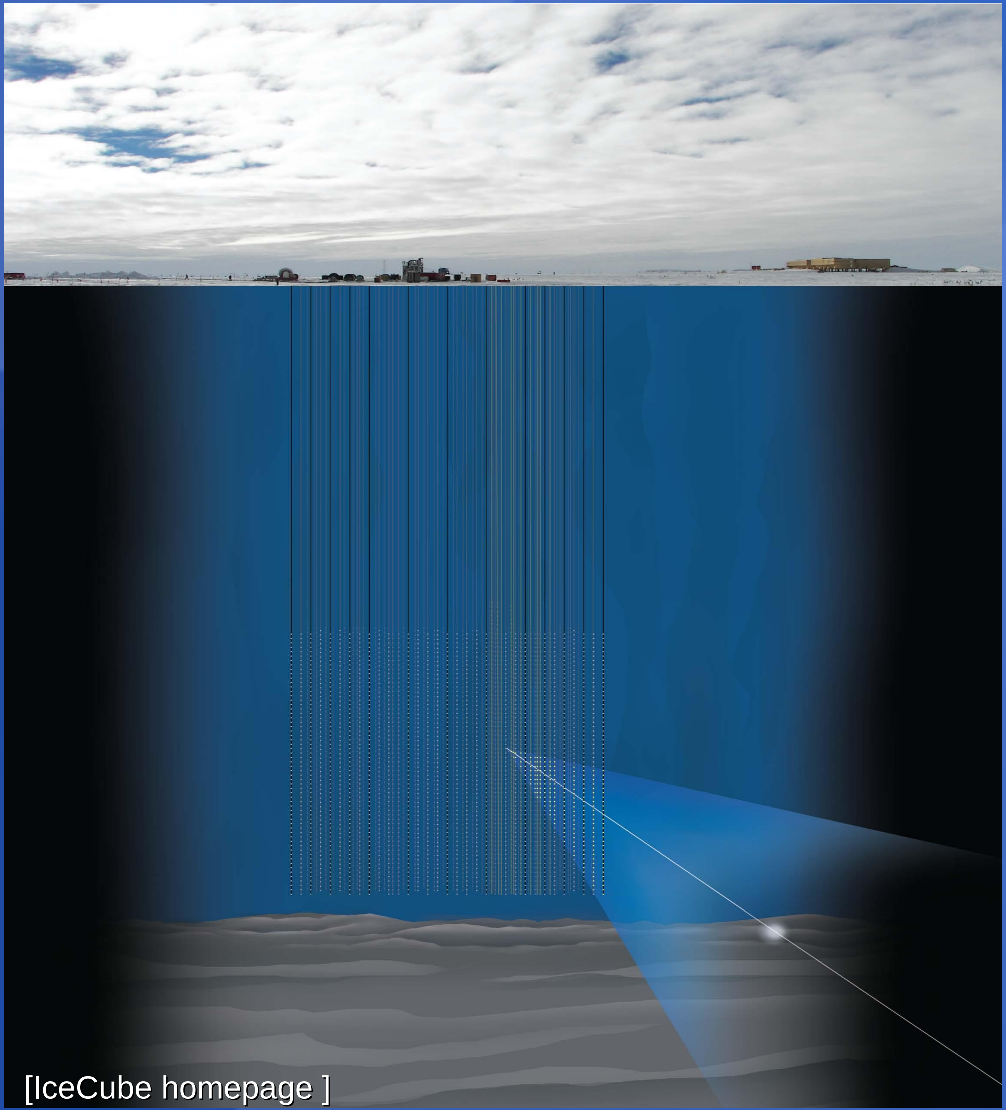
2D non-rotating 15 M_{sun}

IceCube – Cherenkov telescope

- Digital Optical Modules with photo-multiplier tubes.

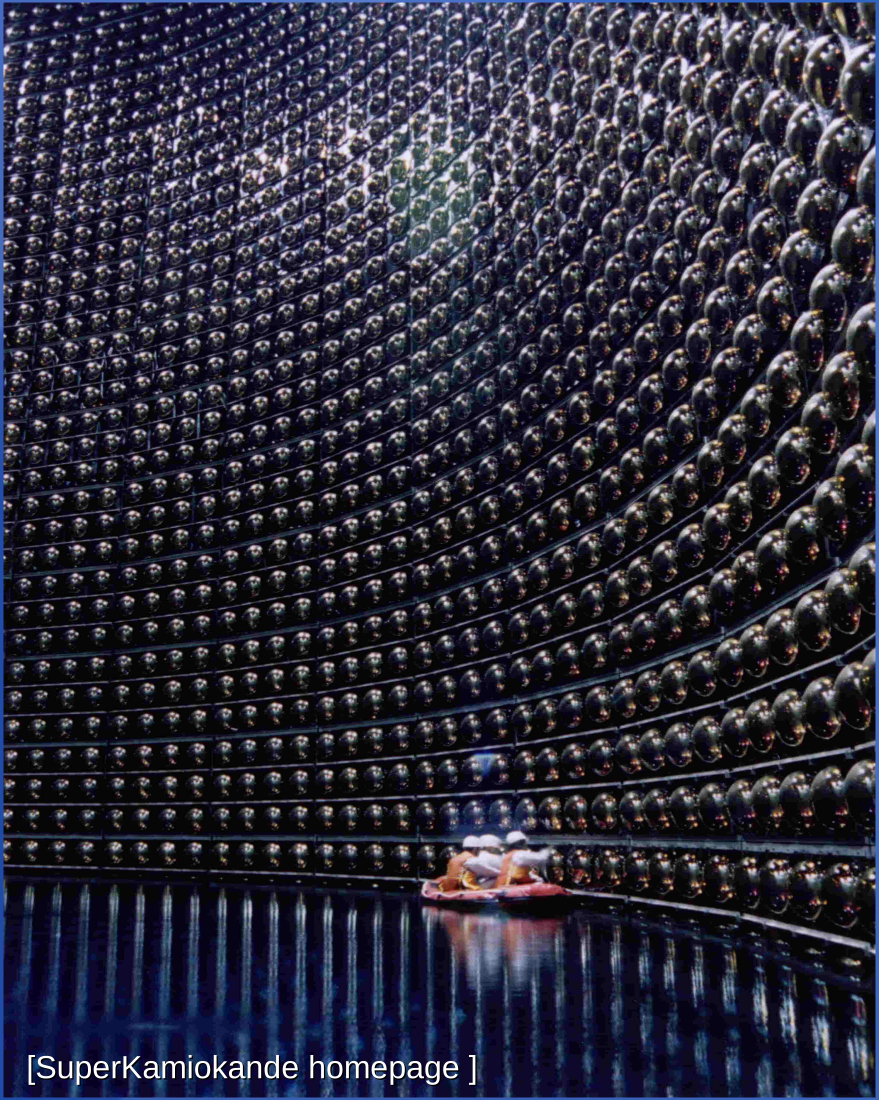
$$\bar{\nu}_e + p \longrightarrow n + e^+$$

- Optimized for energy range:
  - 1 TeV ≤ E ≤ 1 PeV
- SN $\bar{\nu}_e$ energy:
  - E ~ 12 – 18 MeV
- Not entire Cherenkov cone only one photon per interaction → diffuse blue glow of the ice.



IceCube – superiority

- For entire duration ($t \sim 10$ s) of SN we expect $\sim 10^6$ events.
- Factor of 100 more than expected in SuperKamiokande.
- Instantaneous rate for 2D:
  - $\Gamma_{SN} \sim 900\ \mathrm{ms}^{-1}$
- Dark Current noise in IceCube:
  - $\Gamma_{noise} \approx 1340\ \mathrm{ms}^{-1}$
- Looking at time structure of the increased noise.


[SuperKamiokande homepage]

Calculations

Expected eventrate in IceCube:

$$R_{\bar{\nu}_e} = 114\ \mathrm{ms}^{-1} \frac{L_{\bar{\nu}_e}}{10^{52}\ \mathrm{erg\ s}^{-1}} \left(\frac{10\ \mathrm{kpc}}{D}\right)^2 \left(\frac{E_{\mathrm{rms}}}{15\ \mathrm{MeV}}\right)^2$$

$$E_{\mathrm{rms}}^2 = \frac{\langle E^3 \rangle}{\langle E \rangle}$$

- Energy and luminosity data from numerical simulations by the Garching group.

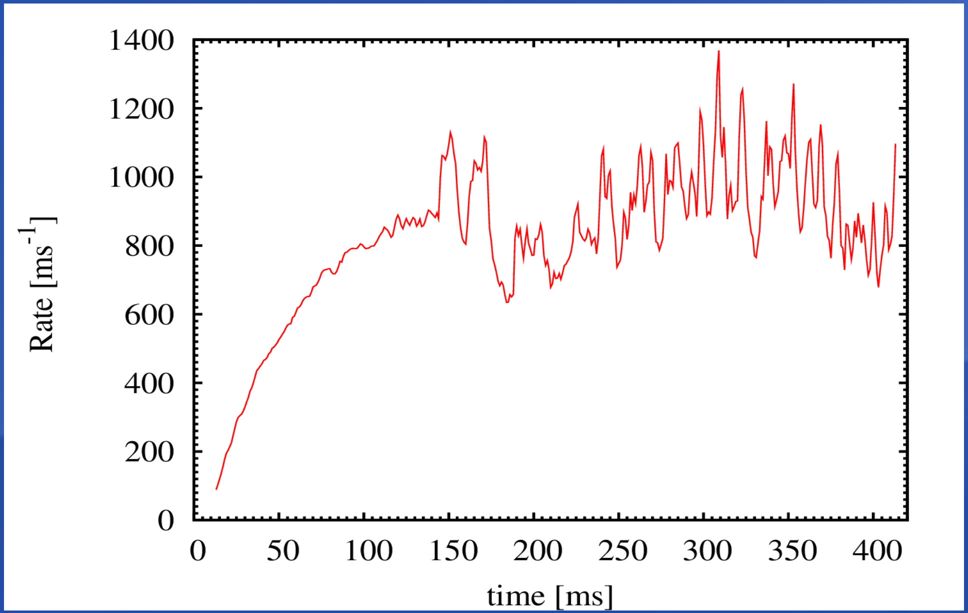
2D:

- Progenitor star; 15 $M_\odot$, non-rotating, soft and stiff EoS.
- Progenitor star; 11.2 $M_\odot$, non-rotating, 3 EoS.

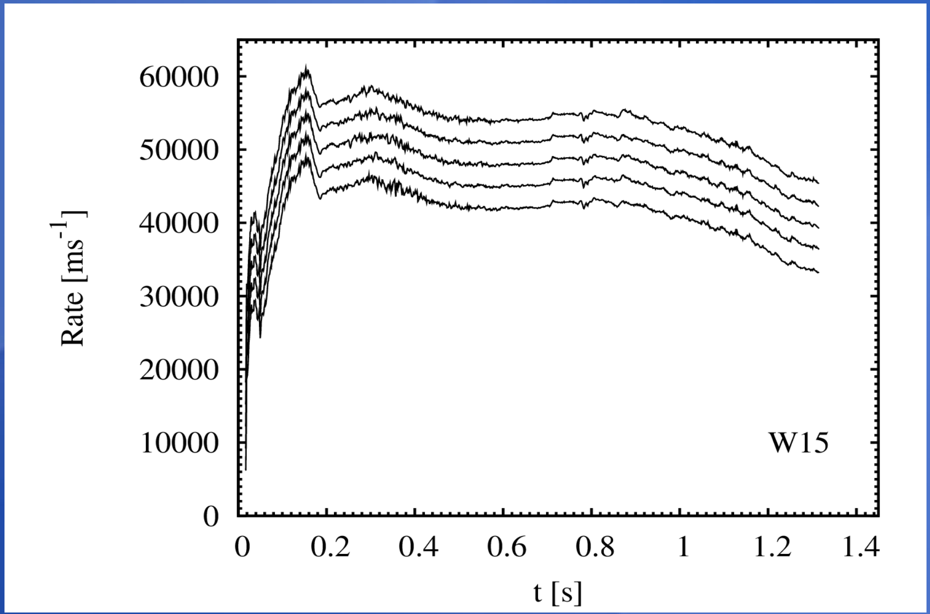
3D:

- Progenitor star: non-rotating, 2 models with 15 $M_\odot$, and 1 model with 20 $M_\odot$.

IceCube event rates



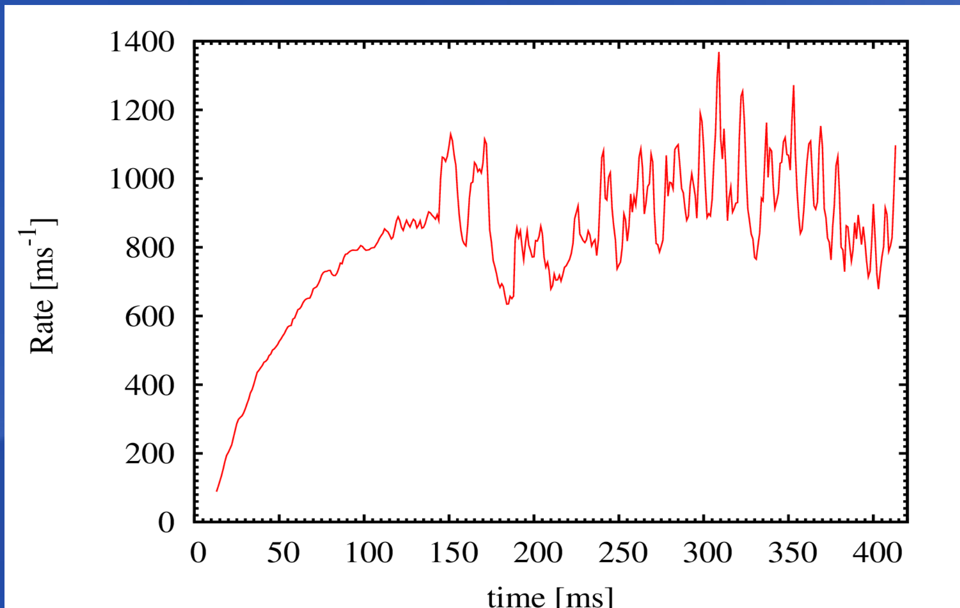
[Lund et al., 2010.]



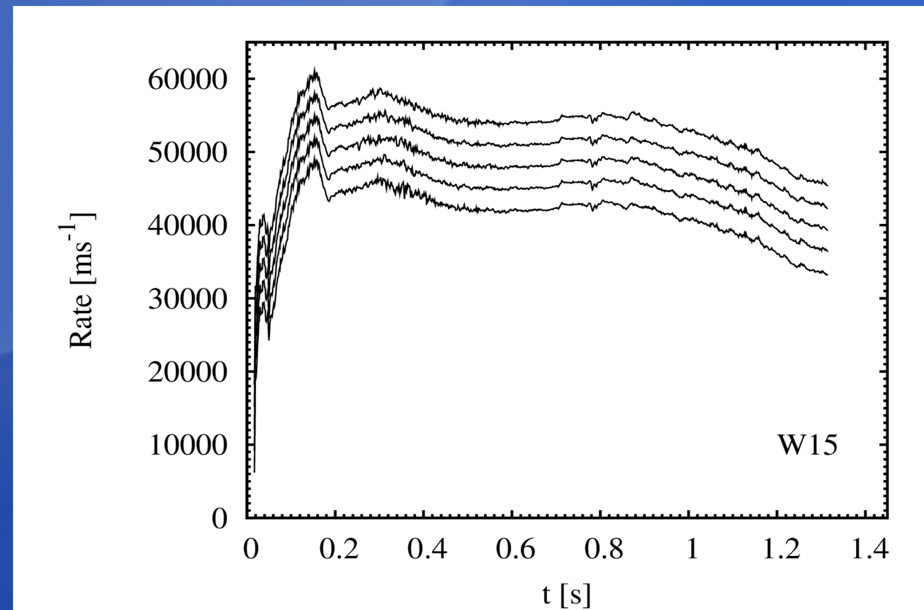
[Lund et al., 2012.]

- Instantaneous rate for 2D at 10 kpc:
  - $\Gamma_{SN, 2D} \sim 900\ \mathrm{ms}^{-1}$
- Instantaneous rate for 3D at 1 kpc:
  - $\Gamma_{SN, 3D} \sim 55000\ \mathrm{ms}^{-1}$

IceCube event rates



[Lund et al., 2010.]

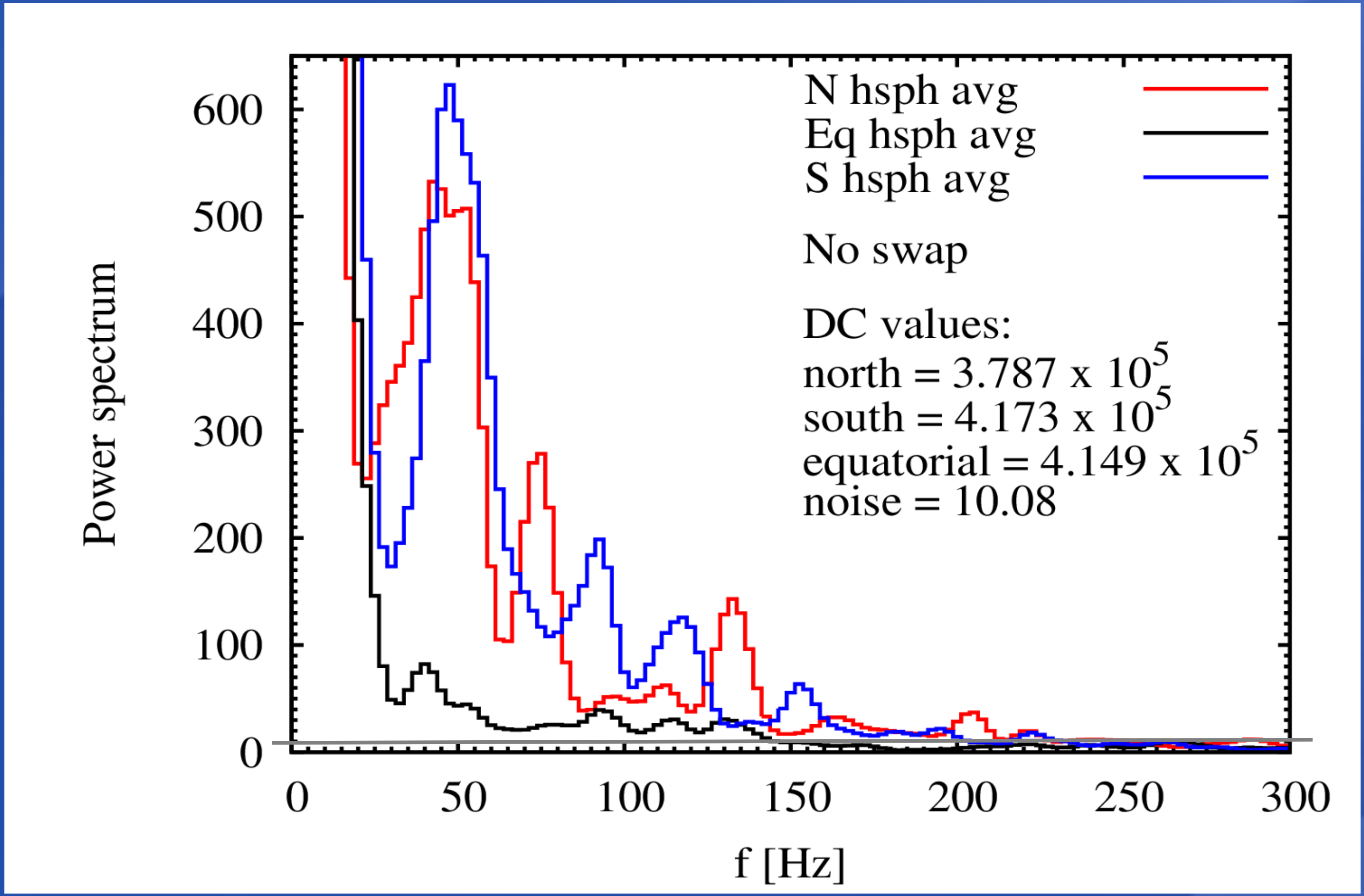


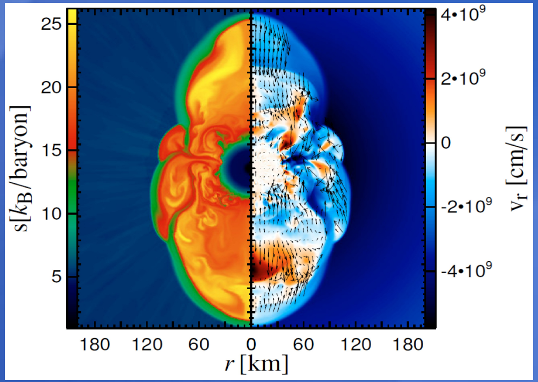
[Lund et al., 2012.]

- Instantaneous rate for 2D at 10 kpc:
  - $\Gamma_{\mathrm{SN,\,2D}} \sim 900\ \mathrm{ms}^{-1}$
- Instantaneous rate for 3D at 1 kpc:
  - $\Gamma_{\mathrm{SN,\,3D}} \sim 55000\ \mathrm{ms}^{-1}$
- Do Fourier transform to look for time structure.

Results - 2D

Non-rotating 15 M_{sun} at 10 kpc





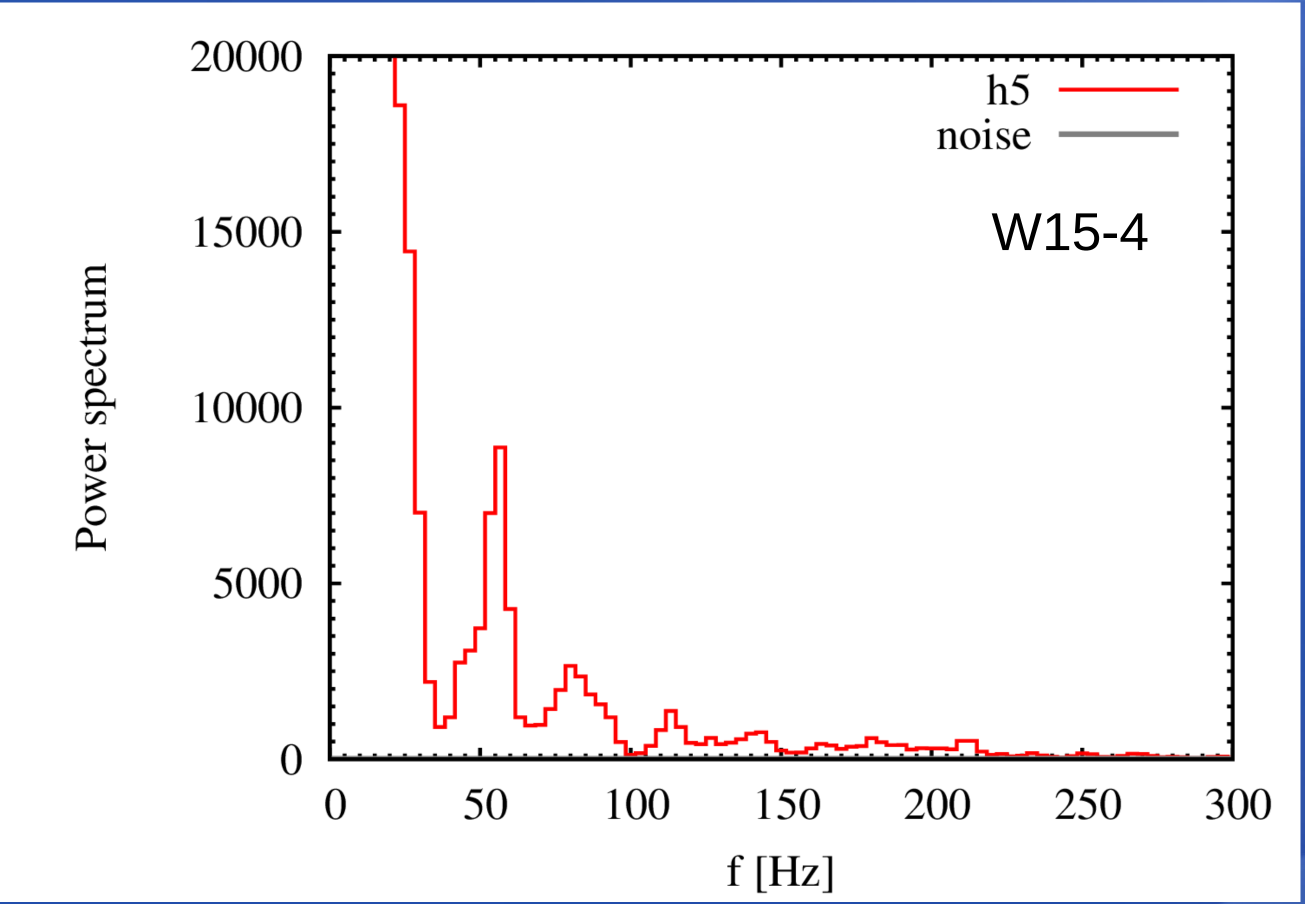
- Hemispherical differences.
- SASI modes:

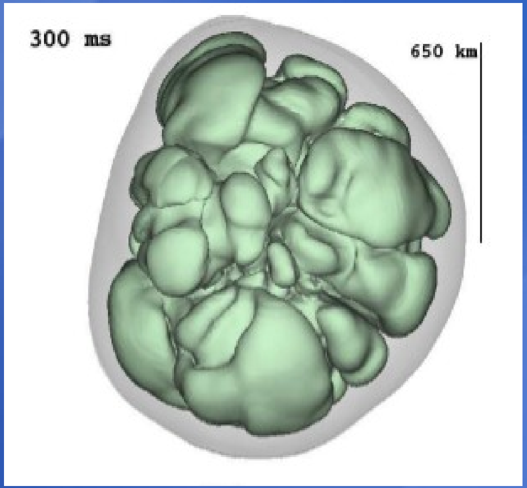
  50 Hz is l = 1

  70 Hz is l = 2

Results - 3D

Non-rotating 15 M_{sun} at 1 kpc





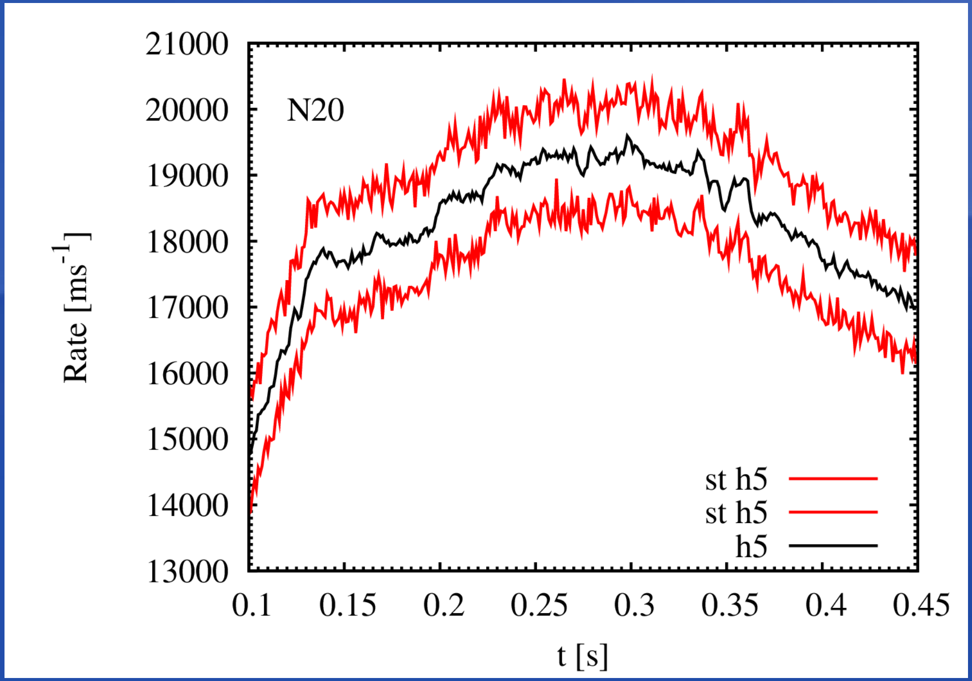
- Minor hemispherical differences.
- SASI modes:

  50 Hz is l = 1

  70 Hz is l = 2

[Lund et al, 2012.]

Stastistical effects



N20 at 2 kpc

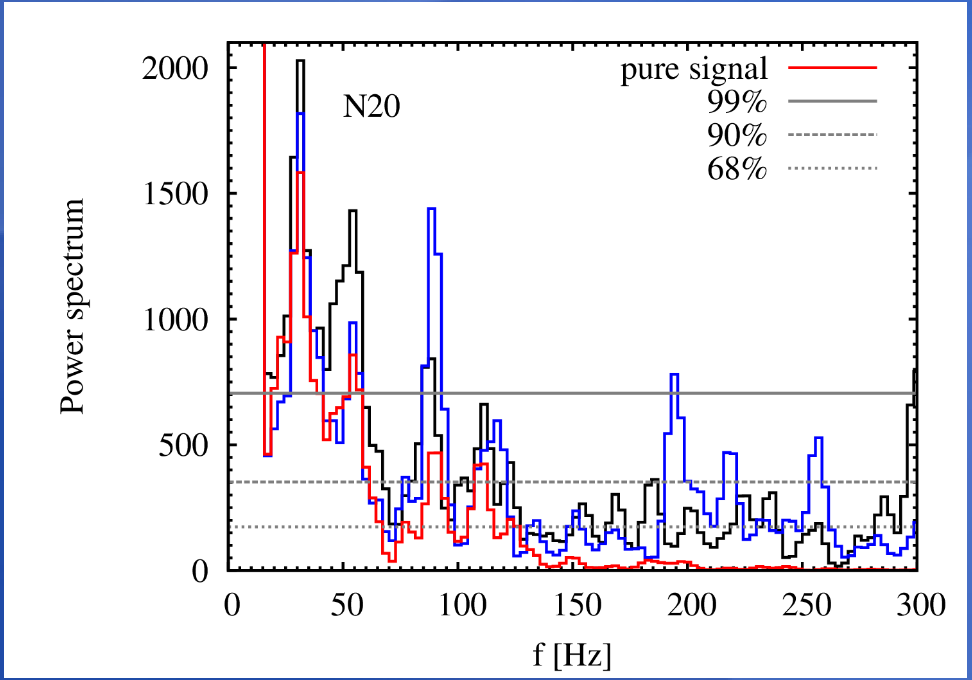
- Statistical fluctuations of the observed signal:

  $N = \sqrt{R}$

- Was ~ 3 % in 2D, compared to 18 % for SASI induced.
- At 10 kpc for 3D would have been ~ 4 %, compared to 1-2% for SASI induced.
- Scales with 1/D, thus less than 1 % at 2 kpc.

Stastistical effects

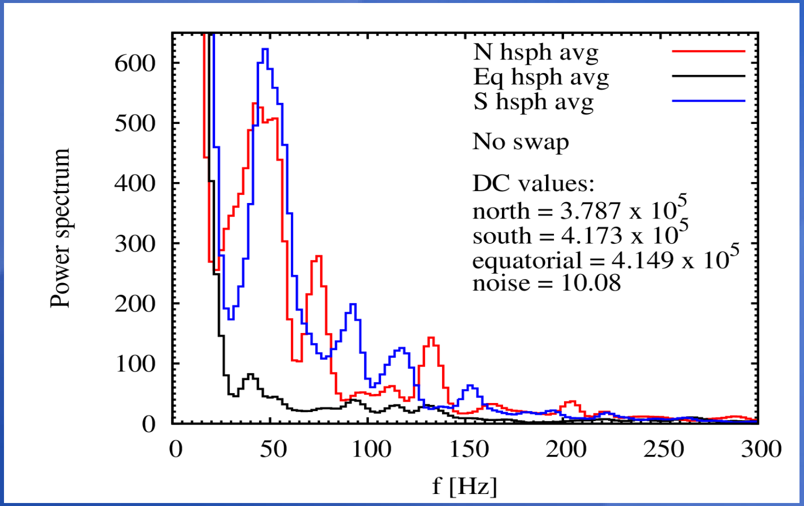
- With given probilities a peak caused purely by statistical fluctuations will fall below gray line levels.
- Peaks reaching above cannot be caused purely by statistics.

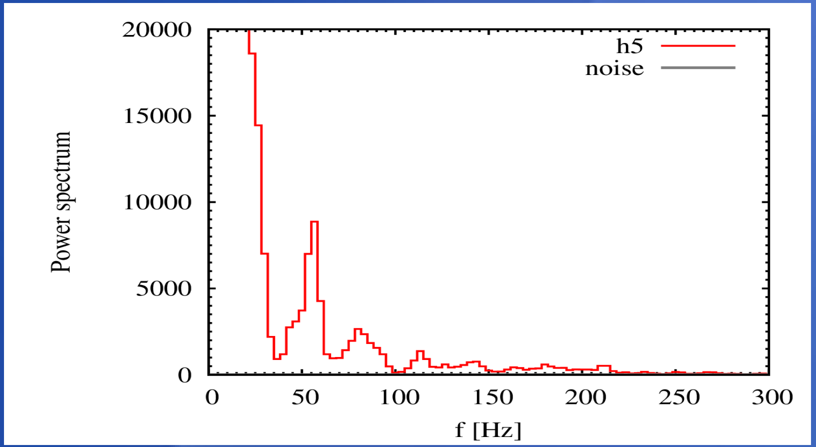


[Lund et al, 2012]

Lessons from early time signals

- SASI effects observable in IceCube, despite energy resolution → better understanding of SN.
- If observed short-lived mechanisms ruled out.
- Signal depends on mass, EoS, rotation, viewing direction and flavor.
- Weaker SASI in 3D models.



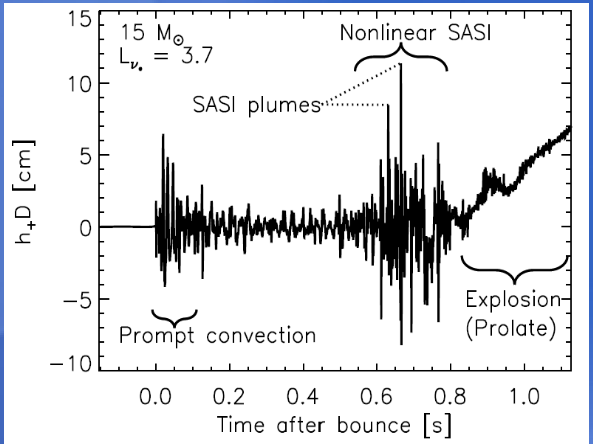


Perspectives

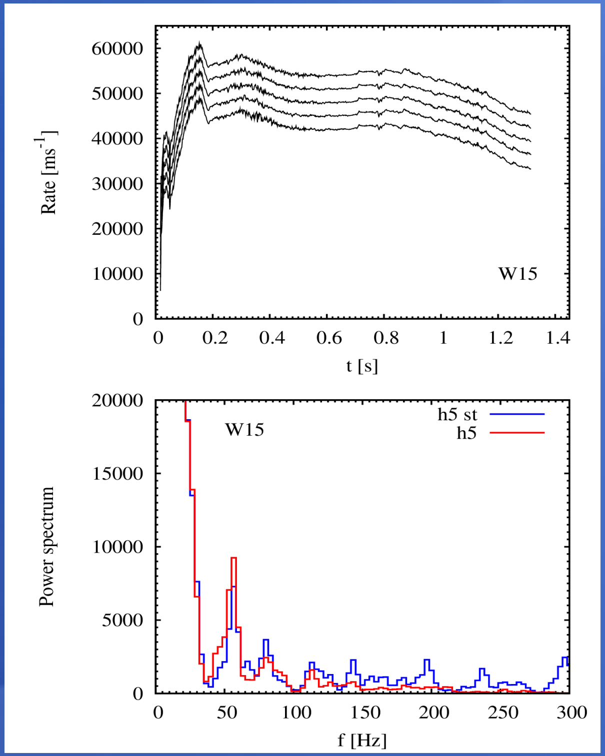
- Investigations give handles on next galactic ccSN:
- Gravitational waves.
- Observational predictions of neutrino signals:

  - Accretion stage fluxes can tell about SASI.

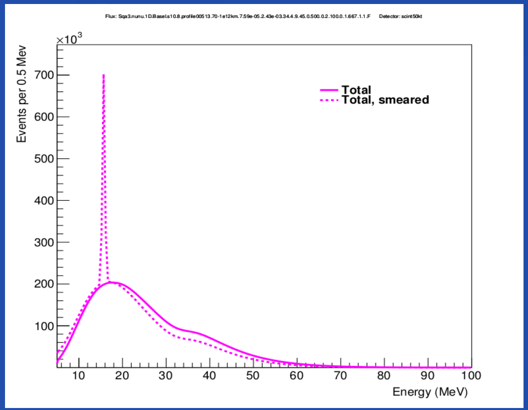
  - Cooling stage fluxes may tell about collective, shock, turbulence and MSW effects.
- Neutrino wind composition may be different → changes expected nucleosynthesis.



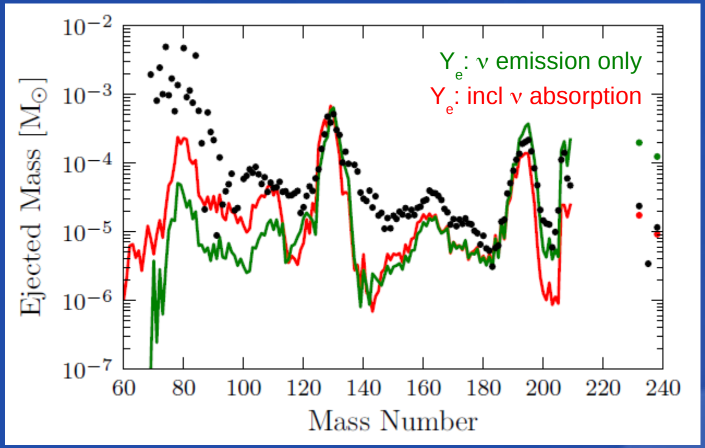
[Murphy et al, 2009]



[Lund et al, 2012]



[Lund & Kneller in prep.]



[Winteler et al, 2012]

Conclusions

- Observing neutrino signals can help us learn about SN and neutrinos:
  - explosion mechanism
  - shock wave
  - collective effects
  - matter effects.
- Need different detector types.

Conclusions

- Observing neutrino signals can help us learn about SN and neutrinos:
  - explosion mechanism
  - shock wave
  - collective effects
  - matter effects
- Need different detector types.

Need new Milky Way SN.

IBD events

PRELIMINARY